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RADIO AIDS TO NAVIGATION REQUIREMENTS: THE 1988 SIMULATOR EXPERIMENT

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16. Abstract

This report describes a man-in-the-loop simulation experiment conducted to assist the U.S. Coast Guard in evaluating a requirement in the 1986 Federal Radionavigation Plan for an 8 to 20 meter (2 drms) system accuracy for piloting in restricted waterways. A variety of system accuracies were evaluated in several visibilities and with several display devices. All system accuracies and device displays supported performance approximating a visual piloting baseline in the straightways. Turn performance was more sensitive to differences among conditions and was very poor in zero visibility. The findings support near-term implementation of such systems as electronic ranges or reduced visibility enhancements, but not as zero visibility/all-weather systems.

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METRIC CONVERSION FACTORS

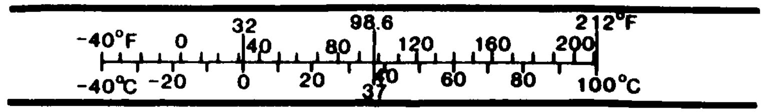
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

BACKGROUND

The question of "How accurate should a radio aids to navigation system be?" has been asked in various forms for many years. The 1986 Federal Radionavigation Plan states that "in the more restricted channels, accuracy in the range of 8 to 20 meters (2 drms) relative to the channel centerline may be required for the largest vessels." However, it also recognizes that a need exists to more accurately determine these system accuracy requirements for various-size vessels which operate within such restricted waters. The primary goal of this experiment was to evaluate the 8 to 20 meter (2 drms) RA system accuracy requirement for piloting deep-draft commercial vessels in narrow channels. The secondary goal was to gain additional insight into the trade-offs among RA system accuracy, display device complexity, and visibility as regards piloting deep-draft commercial vessels in narrow channels.

1988 SIMULATOR EXPERIMENT

In order to investigate these critical issues relating to RA system accuracy, the shiphandling simulator at the U.S. Coast Guard Academy was employed to conduct a man-in-the-loop simulation experiment. Licensed pilots from the Northeast Marine Pilots Inc., who had recent experience on commercial ships in restricted channels, participated as test subjects. These pilots were given a familiarization session with the representative RA devices simulated for evaluation during the experiment. They were then asked to make a number of transits with the various devices under a variety of RA system position accuracies and visibilities. They also made a comparable transit under visual piloting conditions in order to provide a performance baseline.

FINDINGS: SYSTEM ACCURACY, VISIBILITY, AND SHIPHANDLING REQUIREMENTS

- The range of 8-20 meters (2 drms) system accuracy is an appropriate goal for restricted channels. Shiphandling performance with this range of accuracies, measured at the display, approximated the visual piloting baseline.

- In reduced visibility (0.25 nm, or visibility just sufficient to allow an intermittent view of the aids) the entire 8-20 meter spectrum supported straightaway performance that approximated the visual piloting baseline.

- In reduced visibility, turn performance was susceptible to system accuracy. Better accuracy supported turns approximating the visual baseline; poorer accuracy did not.

- In zero visibility/all-weather conditions, turn performance was very poor compared to the visual piloting baseline.

FINDINGS: DISPLAY DEVICES

- In reduced visibility (0.25 nm, or visibility just sufficient to allow an intermittent view of the aids) all the simulated display devices supported straightaway performance as good, or better than the visual piloting baseline.

- In reduced visibility (0.25 nm, or visibility just sufficient to allow an intermittent view of the aids) the graphical displays supported turn performance that approximated the visual piloting baseline, but the digital displays did not.

- In zero visibility/all-weather conditions, turn performance, with the most complex graphical display simulated, was much poorer than the visual piloting baseline.

POTENTIAL OPERATIONAL USES:

- The findings support near-term implementation of systems, like those evaluated, as electronic ranges. As such, they would provide an alternative source of navigational information in straightaways in demanding situations: for example, when aids are removed because of ice or when a few users have special needs. Greater caution is needed for implementation at the upper end of the 8-20 meter range. A variety of display devices would be appropriate.

- The findings support near-term implementation of systems, like those evaluated, as reduced visibility enhancements. They would provide improved performance in visibilities as low as 0.25 nm, or visibility just sufficient to allow an intermittent view of the aids. Greater caution is needed for implementation at the upper end of the 8-20 meter range. Considerations for caution are the relationship of ship size to channel width and the severity of required turn maneuvers. Graphical, but not digital, displays can make a contribution when turns are required.

- The findings do not support implementation of systems, like those simulated, for zero visibility/all-weather navigation. However, the present experiment has identified issues that require further investigation before such implementation. Principal among these are a) the display features or training needed for negotiating turns in zero visibility and b) the need to monitor and possibly meet other traffic in restricted waterways.

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Section 1

INTRODUCTION

1.1 BACKGROUND

The 1986 Federal Radionavigation Plan (FRP)[1] "delineates policies and plans for radionavigation services provided by the U.S. Government to ensure efficient use of resources and full protection of national interests." As part of the planning process, it summarizes the present use of radionavigation services and potential future uses. In a discussion of civilian marine use in harbor and harbor approaches, it makes the point that automated displays are now available to provide the ship's captain, pilot, or navigator with a continual reference of ship position. The principal uncertainty is in the Radio Aid (RA) system accuracy requirements for such use.

As regards RA system accuracy, the FRP states that "in the more restricted channels, accuracy in the range of 8 to 20 meters (2 drms) relative to the channel centerline may be required for the largest vessels." However, it also recognizes that a need exists to more accurately determine these radionavigation requirements for the various-sized vessels which operate in such restricted confines.

During the past several years, shiphandling simulators have been successfully utilized by the Coast Guard within its Waterway Performance, Design and Evaluation Study to establish the relative effectiveness of alternative visual aid to navigation configurations.[2] In keeping with this successful approach, a shiphandling simulator was proposed for this investigation of the critical issues relating to RA system accuracy. The experiment was conducted on the Ship Control and Navigation Training System (SCANTS) located at the U.S. Coast Guard Academy in New London, Connecticut. A generic radio aid device was developed by Ship Analytics, Inc., and interfaced with the simulator. Licensed commercial pilots were asked to make transits with a deep-draft ship in a restricted waterway with a variety of device configuration, positioning accuracies, and visibilities.

1.2 EXPERIMENT GOALS

(A) Evaluate the 8-20 meter (2 drms) RA system accuracy requirement for piloting deep draft commercial vessels in narrow channels.

(B) Gain additional insight into the trade-offs among RA system accuracy, display device complexity, and visibility as regards piloting deep-draft commercial vessels in narrow channels.

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[1]Federal Radionavigation Plan. United States Department of Defense, DoD-4650.4, and United States Department of Transportation, DOT-TSC-RSPA-87-3, Washington, D.C. 20590, 1986.

[2]Smith, M.W., K.L. Marino, and J. Multer. Short Range Aids to Navigation Systems Design Manual for Restricted Waterways. CG-D-18-85, United States Coast Guard, Washington, D.C. 20593, June 1985 (NTIS AD-A158213).

1.3 THE SHIP CONTROL AND NAVIGATION TRAINING SYSTEM (SCANTS)

The Ship Control and Navigation Training System (SCANTS) is one of a number of simulators, built by Ship Analytics, with the capability to support both training and operational research. The shiphandler directs the navigation of the vessel from a mock-up of a pilothouse, which contains all relevant navigational instrumentation. Real-time computer-generated graphics provide the visual scene presentation. SCANTS' capability to simulate the marine environment for the shiphandler is supported by the validation of a similar Ship Analytics simulator during the previously-mentioned Waterways Performance, Design and Evaluation Project.[3] Both simulators use the same techniques for visual scene generation, hydrodynamics, data collection, and a variety of other functions. The SCANTS shiphandling simulator is described in more detail in Appendix A.

[3] Ibid.

Section 2

THE SIMULATOR EXPERIMENT

2.1 GENERAL

In order to accomplish the goals identified in Section 1.0, a comprehensive man-in-the-loop experiment was developed and conducted on the full-mission shiphandling simulator located at the U.S. Coast Guard Academy (SCANTS). As previously noted, a generic Radio Aid (RA) device was developed by Ship Analytics and installed on the bridge of the simulated ownship. Pilots from Northeast Marine Pilots, Inc., who regularly handle a variety of vessels in Narragansett Bay and other southern New England pilotage waters, were employed as test subjects. This section of the report describes the design of the experiment, the accuracy levels of the RA system, the design of the RA devices, the specific qualifications of the test subjects, and the various procedures employed during the experiment.

2.2 EXPERIMENTAL DESIGN

The experimental design developed for this investigation is illustrated in Figure 2-1. One test scenario, which was set in the generic geographic data base that had been developed for the previously-mentioned Waterway Performance Study, was run by test subjects under a variety of conditions. These conditions involved different levels of the following variables, all of which are relevant to the radionavigation problem:

- RA System Accuracy (Random Error)
- RA System Accuracy (Bias Error)
- Display Device Complexity
- Visibility

Each of these variables is discussed in depth within the following sections. It should be noted that the same test scenario was also run under normal visual piloting conditions in order to provide a basis for the relative comparison of radio aid performance versus the currently-acceptable risk, visual baseline standard. The specific experimental objectives and their associated performance comparisons, which this experimental design was designed to analyze, are identified in Table 2-1.

2.3 RADIO AID SYSTEM ACCURACY

Prior to defining the various levels of RA system accuracy, which were investigated during this experiment, several points need to be clarified. First, the accuracy of a RA system for vessel navigation is a function of several factors (see Figure 2-2). These factors include the accuracy of the RA signal itself, the characteristics of the receiver, the design of the signal-processing hardware, and the update rate of the display device. For purposes of this man-in-the-loop experiment, the critical accuracy is the accuracy of ownship position which is presented on the RA device display. The process by which the signal reaches the display, and the accuracy of the

RADIO AIDS EXPERIMENT

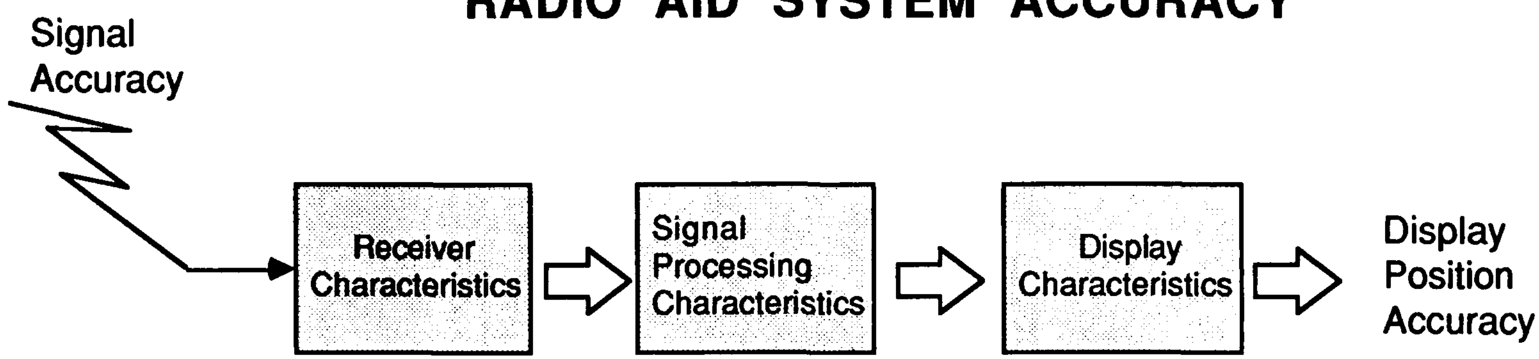
VISUAL BASELINE: Sc. E1						
RADIO AID VARIATIONS:						
	VISIBILITY					
	0.25 nm			zero		
RANDOM ERROR	**BIAS ERROR**					
	Zero	16 m	32 m	Zero	16 m	32 m
	<u>Device</u>					
Display: (10m 2 drms) Signal: (64m 2 drms)	A Sc. E2	Sc. E4	Sc. E7	----	Sc. E8	----
	B ----	Sc. E5	----	---	----	----
	C ----	Sc. E6	----	----	----	----
Display: (18m 2 drms) Signal: (128m 2 drms)	A Sc. E3	----	----	----	----	----
	B ----	----	----	----	----	----
	C ----	----	----	----	----	----

Figure 2-1: Design of 1988 Radio Aids Experiment

TABLE 2-1: EXPERIMENTAL OBJECTIVES AND PERFORMANCE COMPARISONS

Objective: Evaluate Effect of Random Error	
Comparisons:	• Scenario E2 versus Scenario E3 • Scenario E2 versus Scenario E1 • Scenario E3 versus Scenario E1
Objective: Evaluate Effect of Bias Error	
Comparisons:	• Scenario E4 versus Scenario E2 • Scenario E7 versus Scenario E4 • Scenario E7 versus Scenario E2 • Scenario E2 versus Scenario E1 • Scenario E4 versus Scenario E1 • Scenario E7 versus Scenario E1
Objective: Evaluate Effect of Device	
Comparisons:	• Scenario E4 versus Scenario E5 • Scenario E5 versus Scenario E6 • Scenario E4 versus Scenario E6 • Scenario E4 versus Scenario E1 • Scenario E5 versus Scenario E1 • Scenario E6 versus Scenario E1
Objective: Evaluate Effect of Visibility	
Comparisons:	• Scenario E4 versus Scenario E8 • Scenario E4 versus Scenario E1 • Scenario E8 versus E1

RADIO AID SYSTEM ACCURACY



Definition: Radio Aid System Accuracy = Display Position Accuracy

If Radio Aid System Accuracy Requirement = 8-20 meters (2 drms)*

Then Display Position Accuracy Requirement = 8-20 meters (2 drms)

*Note: 1986 Federal Radio Navigation Plan

Figure 2-2: Measurement of Radio Aid System Accuracy initial signal itself, is of secondary interest since the type of RA system can change (i.e., LORAN "C", GPS) and the sophistication of the receiver and processing technology within a particular system can advance dramatically. In other words, the focus of this experiment is on the question, "what positional accuracy does the human operator (namely the shiphandler/navigator/pilot) require to safely navigate, via the RA display, within these types of restricted channels?"

The second point that needs to be discussed is that RA system accuracy can be broken down and analyzed into two components: (a) random error and (b) bias error. Both of these types of error are defined and discussed in detail within the following sections of the report.

2.3.1 Random Error

Random error is the component of RA system positional error that fluctuates continually as the RA system is used during the navigation process. This unwanted error (i.e., noise) may originate from a variety of sources, both man-made and natural.[4] Strictly speaking, it does not have a readily definable pattern. However, statistical techniques have been successfully employed to define its probabilistic boundaries and model the frequency of occurrence of various errors within these boundaries. For two-dimensional navigation systems, the 2 drms (distance root mean square) uncertainty estimate is used.[5] For purposes of this experiment, random error was modeled on a north/south and an east/west set of axes.

The two levels of random error investigated during this experiment were (a) 10 meters (2 drms) and (b) 18 meters (2 drms). These values were selected based on several considerations. First, the 8-20 meters (2 drms) FRP goal established the approximate magnitude of the random error to be investigated. Second, previous research conducted during earlier phases of the Waterway Performance Study provided an impetus to use the specific values of 10 meters (2 drms) and 18 meters (2 drms). During this previous research, the necessary off-line analyses had been completed to relate these specific display accuracies with their associated input signal accuracies for typical receiver and signal processors.[6] This previous analysis indicated that to obtain a display accuracy of 10 meters (2 drms), using available 1980-1990 technology, a signal of 64 meters (2 drms) accuracy would be required. To obtain a display accuracy of 18 meters (2 drms), a signal of 128 meters (2 drms) would be required. It should be noted that the simulated tracker involved an alpha-beta filter with a 24 sec rise time, ownship dead-reckoning, and gyro aiding.

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[4]Bowditch, Nathaniel. American Practical Navigator. Defense Mapping Agency Hydrographic Center, United States Department of Defense, Washington, D.C., 1977.

[5]Federal Radionavigation Plan. United States Department of Defense, DoD-4650.4, and United States Department of Transportation, DOT-TSC-RSPA-87-3, Washington, D.C. 20590, 1986.

2.3.2 Bias Error

Bias error is the component of RA system positional error that is essentially constant over the duration of a vessel's transit within a specific waterway. It could be the result of any number of factors, including but not limited to seasonal atmospheric variations, daily atmospheric variations, transmitter adjustments, receiver characteristics, etc. For purposes of this experiment, the magnitude and direction of the bias error was known by the pilot but was not removed from the displayed position. In other words, it was assumed that the pilot was able to at least determine the bias error prior to the transit. It was also assumed that any large spatial variations of the signal accuracy within the waterway (i.e., grid warp) had been previously removed via geographic survey techniques.

Two levels of constant bias error were investigated during the experiment: (a) 16 meters and (b) 32 meters. While the previous research provided considerable guidance for the selection of levels of random error, there was little guidance for the selection of levels of bias error. Levels were tentatively selected with the intention of running two preliminary subjects and assessing their performance and subjective reactions. For the familiarization scenarios in a simulated Providence, the researchers examined the range of signal variations obtained at the near-by Bristol, R.I., LORAN-C monitoring station over a two-year period.[7] The largest observed error there was 104 meters, suggesting the possibility of a worst-case bias error of one half the channel width (i.e., 300 feet in 600 foot channel). The first two pilots were adamant about not piloting a vessel with an uncorrected displayed position close to or outside the channel boundaries. This condition was then dropped from the experiment and replaced with a 33 meters bias, the worst-case predicted differential LORAN-C error for the Bristol station. Other bias errors -- 20 meters for Providence and 16 and 32 meters for the experimental Stone Channel -- were then arbitrarily selected within the boundaries of each channel. These bias errors were better accepted by the pilots and were retained.

2.3.3 Summary

Figure 2-3 summarizes the random and bias accuracy levels investigated during this RA experiment. It is important to re-emphasize that RA system positional accuracy as measured at the display was evaluated in this simulator experiment. The signal accuracy required to obtain these positional accuracies at the display can vary based on the type of RA system employed and the sophistication of the technology within said system.

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[6]Cooper, R.B., K.L. Marino, and W.R. Bertsche. Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-2 Experiment, United States Coast Guard, Washington, D.C. 20593, July 1981.

[7]Blizard, M.M., D.C. Slagle, K.P. Hornburg. Harbor Monitor System: Final Report. United States Coast Guard Research and Development Center, Groton, Connecticut 06340, December 1986.

RADIO AIDS SYSTEM ACCURACY SUMMARY 1988 EXPERIMENT

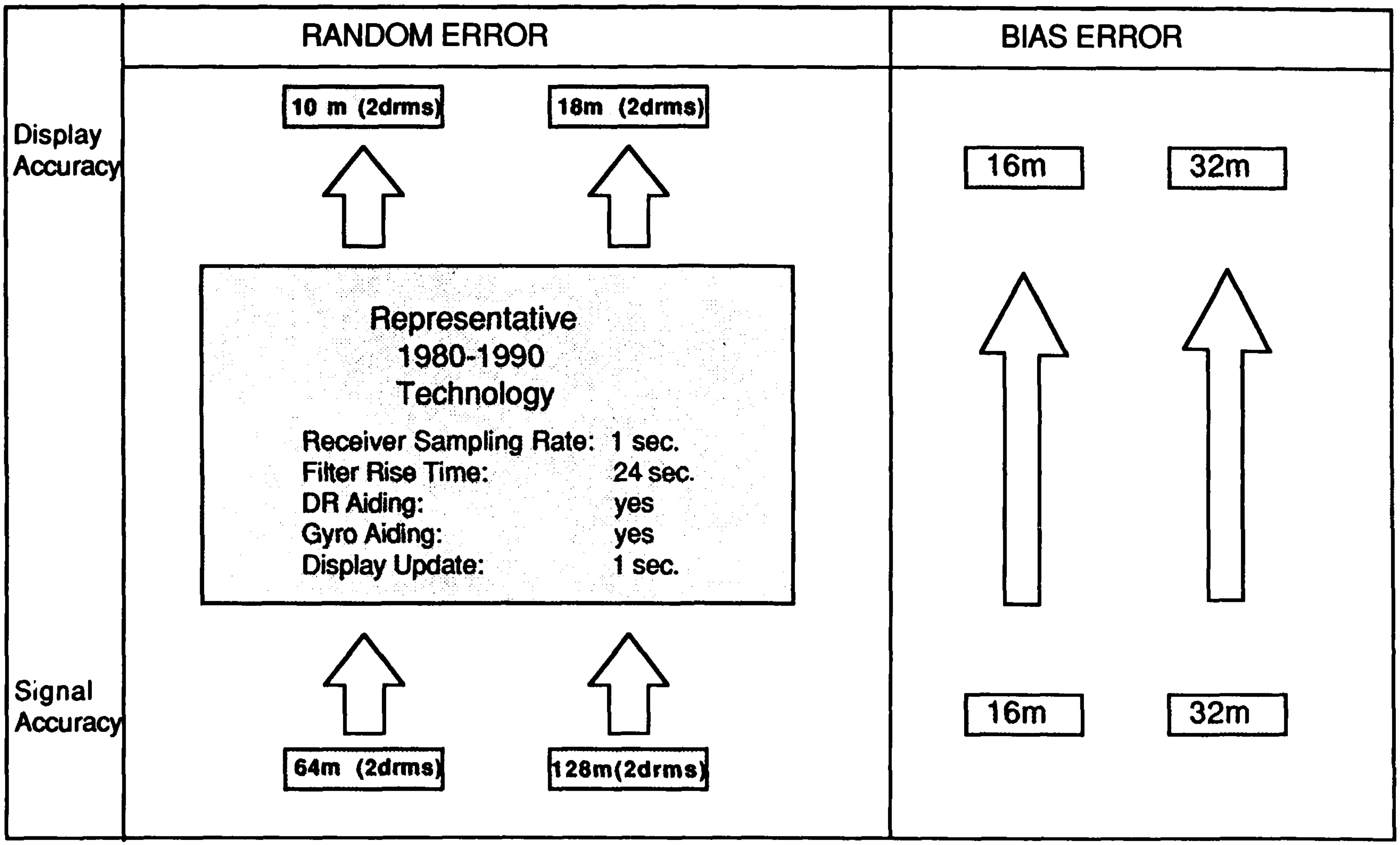

Figure 2-3: Radio Aid System Accuracy Levels for 1988 Experiment

Radio Aids 0026

2.4 DISPLAY DEVICES

To meet the primary experimental objective of evaluating system accuracy, it was necessary to make a number of decisions about the display device(s), which were developed for use within this experiment. A number of sources were considered in selecting the features and capabilities of these devices. The first consideration was the experience gained via two prototype devices developed in 1981, by the U.S. Coast Guard, and tested at sea.[8] The Precision Intracoastal LORAN Translocator (PILOT) had a graphical display; the Portable LORAN-C Assist Device (PLAD) had a digital-only display. A second consideration was the 1981 Radio Aids experiment, which evaluated a variety of graphical and digital displays.[9] Because the at-sea prototypes and the experiments were directed at the same time and by the same U.S. Coast Guard representatives, the displays in the two situations had much in common. A third consideration was the type of device technology that is commercially available at the present time.

The simulator devices which were evaluated within this experiment were not meant to imitate any one device, but to be generally representative of three different classes of devices, each with different cost and operational implications. (See Figure 2-4). Device A was meant to be representative of several costly devices designed for permanent installation on commercial ships, taking input from a variety of ship's indicators. They allow the selection by the user of a variety of graphical and digital display configurations. Two other, less costly, classes of devices were represented by Devices B and C. Device B was meant to be representative of a class of electronic charts, intended for plotting rather than for ship control. Some of these take input from a positioning device; some require that positioning information be typed in by the user. Those that take input from other ship indicators (e.g., gyrocompass) use the input only to display information in alphanumeric form on the screen, not to be included in calculations. Device C was meant to represent navigational devices with all-digital displays. Available commercial devices like this vary widely in their capabilities. The experimental device was designed assuming that they get no input other than radio positioning information and that they can store waypoints and calculate relationships to them.

The general approach to developing the actual devices was to start with the maximum capability, that of Device A. Substantial guidance for the design of Device A was provided by the results of the previously mentioned 1981 Radio Aids experiment. Devices B and C were then designed by omitting some of the features from Device A, bringing the capability down to that of the class of devices each was meant to represent.

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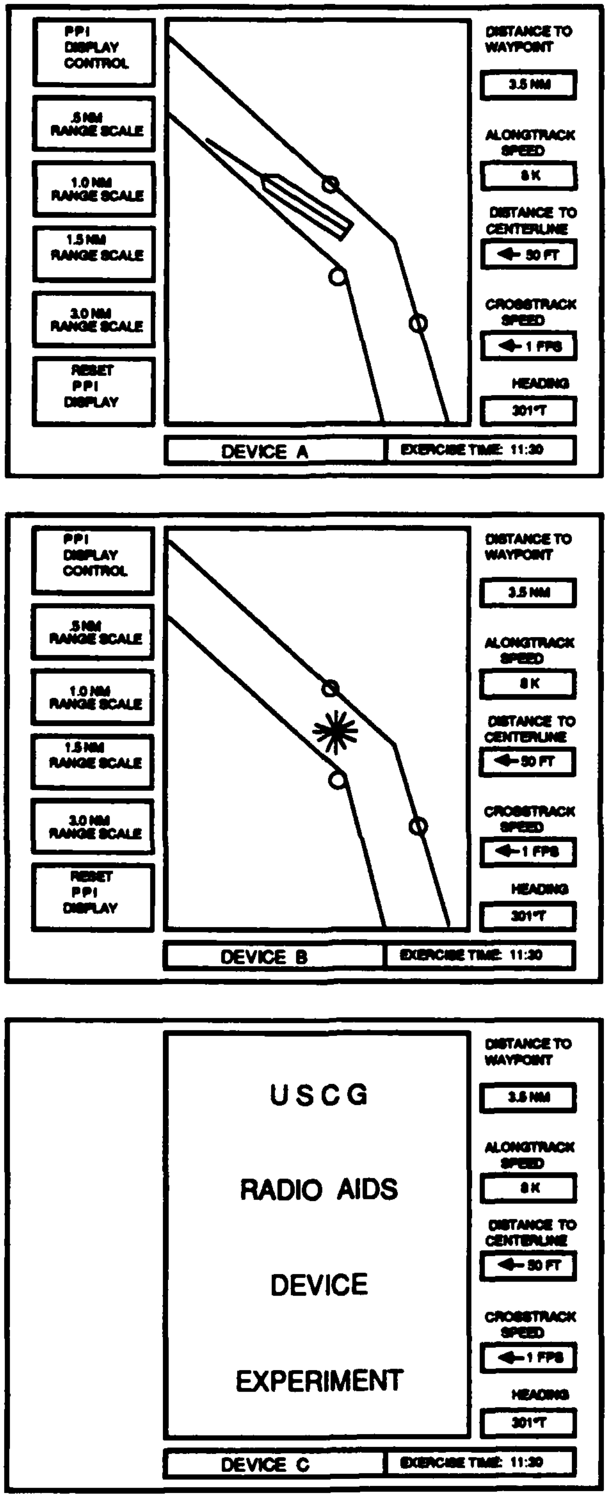
[8] Roeber, J.F. "Black-box Harbor Navigation (Look What The Microprocessor Hath Wrought)" Proceedings of the Marine Safety Council, September/October, 1981.

[9] Cooper, R.B., K.L. Marino, and W.R. Bertsche. Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-1 Experiment. CG-D-49-81, U.S. Coast Guard, Washington, D.C. 20593, January 1981. (NTIS AD-A 106941).



Note: Drawings not to scale

Figure 2-4: The RA Display Devices

The radio aid devices for the experiment were implemented on an IBM/AT - compatible personal computer (PC) with an enhanced graphics adapter (EGA) and a touch-sensitive monitor. Ship Analytics' proprietary software, the Ship Analytics Integrated Learning System (SAILS), provided a framework for the development of the devices. The three experimental "devices" with the features described above were provided as required via the same PC. The PC was interfaced to the simulator for the exercises described in Appendix B and Appendix C.

2.4.1 Device A

Device A presented position information on a plan view display, showing a section of the waterway positioned track-up on the screen. The display depicted landmasses, buoys, major aids, and the channel outline. The ship's outline was shown to scale. The range was selectable, providing 0.5, 1.0, 1.5 and 3 nm from the center of the screen. Digital information was provided to quantify the distance from the channel centerline and from the waypoint at the center of the next turn. Motion information was provided by the ship's movement up the channel in true motion. Speed, both alongtrack and crosstrack, was provided digitally. Heading information was provided by the aspect of the ship in the channel, a heading flash, and heading presented digitally.

2.4.2 Device B

Device B differed from Device A in that the graphical display was oriented north-up, like an electronic chart. The position information presented was probably better than that now available on an electronic chart: these do not provide the shortest range scales and may not provide filtered position accuracy as good as those simulated. Presumably, these features could be added to a moderate-cost device. The motion information was the same as that provided on Device A. Heading information was presented only digitally, assuming that any gyrocompass input was not used for calculating ship aspect. This presentation of heading on the screen was only a convenience since there was a gyrocompass repeater on the bridge.

2.4.3 Device C

Device C presented only digital information distance from centerline, distance from waypoint, alongtrack speed, crosstrack speed. This was information that could be provided without ship input on a portable device. This was what is provided by PLAD, which has been successfully used for the past several years by a pilot, who carrys it with him to board the ship. Again, the filtered position accuracy provided in the experiment may be better than what is provided by some commercial devices.

2.4.4 Familiarization

A fair evaluation of the type of performance to be expected in a harbor/harbor approach with such devices required some practice for the pilots before the taking of formal performance data. Such practice was provided in a harbor with which the pilots were familiar, assuming that this familiarity would maximize the effectiveness of a relatively few practice runs. They began with Device A in unlimited visibility, comparing the situation on the display with the view "out-the-window." Further practice was provided in just enough visibility to see the buoys as they pass, verifying the expected position. After all the planned runs with Device A, they spent some, but less, time with Devices B and C. This familiarization session is described in Appendix B.

2.5 VISIBILITY

Another variable investigated was visibility, which can limit the range at which a pilot can effectively acquire visual aids to navigation such as buoys. These types of visual cues can greatly assist the pilot in periodically verifying the confidence that he should be placing in his radionavigation system. They can also assist him in successfully executing his more difficult shiphandling maneuvers. For example, if visibility is such that the pilot can see the buoys within a turn, it is hypothesized that he will shift to the more familiar cues provided by the buoys during his successful execution of the turn. This shift, which is made possible by sufficient visibility, could potentially impact RA accuracy requirements, since it is generally viewed that one of the navigation/shiphandling tasks which could drive RA system requirements is altering ownship's course within a restricted channel.

Three levels of visibility were investigated during this experiment: (a) unlimited visibility, (b) 0.25 nautical miles (nm) visibility, and (c) zero visibility. The unlimited visibility is appropriate for visual piloting. It was employed during the baseline scenarios to provide a standard with which to compare RA piloting performance. Unlimited visibility also appeared in the experiment for familiarization runs, allowing the pilot to compare his progress on the device with the appearance of the more familiar view "out-the-window."

A 0.25 nm visibility was selected for some RA scenarios. This range of visibility allowed the pilot to visually acquire all of the buoys in the three-buoy turn just prior to reaching the turn initiation point. It also allowed the pilot to visually see each set of gated buoys as he passed through them in the trackkeeping regions (i.e., straight legs).

Finally, some RA scenarios were conducted with zero visibility. This means that only the RA information was available for navigation. These scenarios were the most stringent test of the provided RA information, simulating the ultimate, "all-weather" navigation condition.

2.6 GEOGRAPHIC DATA BASES

2.6.1 Familiarization Session

In order to acquaint the pilots who participated as test subjects with the various important aspects of the simulator environment, including the RA display devices, a one-day program was set-up within a geographic area known to the pilots. Since all test subjects were members of the Northeast Marine Pilots, Inc., the restricted channel into Providence was modeled on the simulator and employed as the geographic data base for the first day's activities (see Section 2.7.2). A graphic illustration of this channel in Narragansett Bay, which vessels transit as they approach the various terminals located in Providence, R.I., appears in Appendix B.

2.6.2 Experimental Session

During the actual Radio Aids Experiment, the test subjects were asked to transit the generic channel, which had been so successfully used during the previously mentioned Waterway Performance, Design and Evaluation Study. A graphic illustration of this channel, which has been named "Stone Channel", appears in Appendix C. It was designed to be representative of restricted channels within U.S. waters that are regularly used by vessels of 30-foot draft or greater. It is approximately 6.5 nm long, with a width of 500 feet, and one 35-degree noncutoff turn. This generic channel was used in this experiment for the same reason it was originally designed and employed during the previous research, namely to allow greater generalization of results than would be possible from the use of a specific real-world waterway.

2.7 TEST SUBJECT PROCEDURES

2.7.1 Qualifications

All test subjects for this experiment were active members of the Northeast Marine Pilots Inc., who had recent experience with commercial ships in restricted channels. Two (2) pilots were run to provide a preliminary evaluation of the simulated RA device(s), ownship's handling characteristics, and the test scenarios. A total of eight (8) pilots were used within the total experiment for data collection purposes.

2.7.2 Familiarization (Day 1)

Each pilot was asked to come to SCANTS for two days. On the first day, he was provided with a briefing on the project as outlined in Appendix B. He was then allowed to handle the simulated ownship in the Providence data base in order to familiarize himself with the general simulator environment and the RA devices. The salient characteristics of each familiarization scenario and the order of these scenarios are provided in the pilot instructions in Appendix B. Subjective data, guided by a questionnaire, was collected from the pilots throughout the day as opportunity and issues present themselves. See Appendix B for questionnaire.

2.7.3 Experiment (Day 2)

On the second day, the actual experiment was conducted and pertinent objective data collected during each test scenario. Each pilot was initially allowed to familiarize himself with the experimental data base (i.e., Stone Channel) prior to the administration of the test scenarios. A brief description of the attributes of these scenarios appears in Appendix C. Once again, subjective data, guided by a questionnaire, were collected from the pilots throughout the day as opportunity and issues present themselves. The questionnaire is also in Appendix C.

2.8 DATA COLLECTION

During the simulation a variety of data were recorded for potential later examination and analysis. They were as follows:

a. Computer-Recorded Measures. As the "ship" transited the channel, its crosstrack position was recorded as a function of alongtrack position. These measures formed the primary data of the experiment. Their use is described in the following sections. The computer also recorded other ship status measures, including: speed, yaw rate, heading, course, rudder angle, and engine revolutions per minute.

b. Operator-Entered Measures. The pilot's helm orders -- course, rudder, and engine order telegraph -- were entered at the terminal by the simulator operator. These orders were recorded by the computer along with measures of ship's position and status.

c. Pilot's Subjective Reactions. The pilot's comments and reactions to all aspects of the simulation were noted by the researcher who was conducting the experimental runs. The standardized questions that were used to guide the discussion appear in Appendices B and C.

2.9 DATA REDUCTION AND DESCRIPTION

After the simulation phase of the experiment, the ship position measures were accessed and subjected off-line to a number of calculations and plots. Initially, the ship positional data within the channel for each experimental run are plotted on the same plan-view geographic chartlet. Appendix D contains these "composite" track plots for each of the experimental scenario.

A second type of presentation is the "combined" plot, which appears in Appendix E for each scenario. The performance for the eight transits in each scenario is statistically summarized by calculating the mean and standard deviation of the eight crosstrack positions of ownship's center of gravity, at individual "data lines" placed at 475-foot intervals along a channel. These statistical data are presented on the three-axis format in Appendix E. The placement of the data lines is indicated by the tick marks along the channel edge. Such plots provide an illustration of the crosstrack mean and standard deviation as a function of alongtrack distance or data line (see top two axes). The mean and standard deviation can then be combined to provide a graphic envelope of expected performance within the channel boundaries. The "envelope" on the third (bottom) axis is formed by the mean with two standard deviations to either side. This envelope represents 95 percent of expected transits for the tested conditions.

2.10 DATA ANALYSIS

The ship position data were then subjected to a number of further manipulations to produce the data tables that are presented in Appendix F. First, for each scenario, a data line was selected from the plots in Appendix E to represent each of the maneuvers required for the transit of the waterway. Second, statistical tests were done between representative data from each pair of scenarios to be compared. Last, a performance index, the relative risk factor (RRF), was calculated for each selected data line. Each of these steps within the analysis is described in more detail below.

2.10.1 Selection of Representative Data by Region

The numerical data are not reported for each data line. Rather, values were selected to represent each of five regions in the transit as it appeared in the combined plot. In order of occurrence in the transit, the regions were 1) recovery to centerline, 2) trackkeeping, 3) turn pullout, 4) recovery to centerline with a second current condition, and 5) trackkeeping on the centerline with a second current condition. A value was selected as characteristic of the ship maneuver being performed in the region.

- For a turn region a value was selected in the turn pullout at the point in the transit were the crosstrack acceleration toward the outside edge of the channel approaches zero. Presumably, this point is the maximum risk of grounding due to turn forces. For an example, see the plot on page E-2. There, the selected value was at Data Line 3, approximately two ship lengths past the turn apex.

- For a recovery region a value was selected where the mean shows a large crosstrack velocity and the standard deviation is high. If several data lines appeared appropriate, the one with the highest RRF was selected. For the example on page E-2, Data Line 6 was selected to represent recovery against the current in Leg 2.

- For a trackkeeping region a value was selected where the mean and standard deviation approximate a constant level or "steady state". With a substantial crosscurrent or with staggered buoys, trackkeeping may not be substantially different than the recovery region. For the example on page E-2, Data Line 18 was selected to represent trackkeeping with the decreasing crosscurrent in Leg 2.

2.10.2 Statistical Tests

The selected means and standard deviations from two different scenarios were compared by statistical tests. First, the standard deviations were compared as variances, using an F-test. If these were not statistically different (i.e., the variances of the two samples were homogeneous), the means were compared using a t-test. Both of these tests are frequently used tests. One description of them appears in McNemar.[10]

[10]McNemar, Q. Psychological Statistics, Fourth Edition, John Wiley and Sons, Inc., New York, 1969.

Statistical significance means that a difference as large as that observed between two scenarios can be expected by chance with only the small probability specified in the table. Such small probabilities mean it is likely that the hypothesized mechanism (e.g., 0.25 nm versus zero visibility) is responsible for the observed difference. Without statistical significance, any differences are more likely to have occurred by chance.

2.10.3 The Relative Risk Factor

The previously mentioned Aids to Navigation System Design Manual makes use of an index, the Relative Risk Factor (RRF). This index takes into consideration the mean and standard deviation of vessel tracklines, ship dimensions, ship aspect, and channel width to produce a number which is proportional to the probability of grounding for the simulated conditions. The RRF is operationally defined by the sample calculation in Table 2-2 which is taken from the Design Manual, Section 2. RRF's have been calculated in Appendix F for each data line analyzed within the experimental scenarios. The interested reader is referred to the Aids to Navigation System Design Manual for a more extensive discussion of the RRF index.

TABLE 2-2. SAMPLE CALCULATION OF RELATIVE RISK FACTOR (RRF) IN THE RECOVERY REGION*

SHIP PARAMETERS

Ship size	30,000 deadweight tons
Ship length	590 feet
Ship beam	85 feet
Crosstrack current velocity	0.25 knots
Transit speed	6 knots
B' (feet)	54.79 feet

CHANNEL PARAMETERS

Channel width	500 feet

SAMPLE CALCULATION OF RRF: Crab angle, 2-5 degrees; gated aids; day

[W/2) - (MN) - (B')]/(SD) = (NS)
[(500/2) - (97) - (54.79)]/(34) = (2.89)

[(W/2) + (MN) - (B')]/(SD) = (NP)
[(500/2) + (97) - (54.79)]/(34) = (8.59)

(PS) + (PP) = (RRF)
(0.0019) + (0.0000) = (0.0019)

reminder:
W: channel width
MN: mean
B': adjusted beam/2
SD: standard deviation
NS: SDs to starboard
NP: SDs to port
PS: prob to starboard
PP: prob to port
RRF: relative risk factor

* This table is taken from the SRA Design Manual, Page 2-17 and shows the standard ship dimensions used there.

Section 3

EXPERIMENTAL RESULTS

3.1 GENERAL

This section describes an analysis of the observed performance for the eight experimental scenarios which are identified in Section 2.2 and summarized in Figure 2-1. Performance for each scenario is illustrated first, in Appendix D, by a composite turn plot showing the eight subjects' ship tracks through the most difficult part of the transit, and second, in Appendix E, by a combined plot showing the mean, standard deviation, and an envelope for the eight transits. (These procedures were described in Section 2.9.)

The analysis was organized in accordance with the specific experimental objectives summarized in Table 2-1. Each comparison listed in the table is represented in Appendix F by the particular descriptive statistical data obtained for the two relevant scenarios, calculated RRFs for these data, and statistical tests where appropriate. (These procedures were described in Section 2.10.)

3.2 RADIO AID SYSTEM ACCURACY

3.2.1 Random Error

Higher random error results in greater ownship track variability and hence greater risk. (See Table F-1). Specifically, the pilots handled ownship in a more accurate and consistent manner when the ownship positional error at the device display was 10 meters (2 drms) as compared to 18 meters (2 drms). Earlier experimentation on the effects of random error[11] indicated that pilots successfully "filter" actual ownship position from the "jitter" affecting ship tracks, when the error was 10 m (2 drms) or less. These new data suggest that the 18 m (2 drms) may exceed this ability.

Employment of a RA device, with an error of less than 10 meters (2 drms), can result in improved performance over visual piloting. (See Table F-2). Specific benefits include (a) quicker recovery to the desired track (e.g., channel centerline) after completion of a turn and (b) more accurate trackkeeping in straight legs when a crosscurrent results in ownship having a significant crab angle. This latter benefit is discussed in detail within Section 3.3. It is important to note at this point, however, that more accurate trackkeeping to the channel centerline, while presented as a positive attribute here, must be used with caution in the presence of other traffic. The importance of integrating accurate ownship positional information with pertinent information on traffic vessels was re-iterated many times during the pilot debriefing sessions.

[11] Cooper, R.B., K.L. Marino, and W.R. Bertsche, Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-2 Experiment. CG-D-50-81, (NTIS AD-A106672).

Although RA navigation performance with the largest random error 18 meters (2 drms) resulted in statistically poorer performance then the visual piloting, the only potentially troublesome area appears to be the turn region. (See Table F-3). As regards this finding, two points should be carefully clarified. First, the fact that RA piloting performance with the 18 meters (2 drms) was poorer than the visual piloting does not mean it was unacceptable. The relative risk factor (RRF) levels in each of the regions (except for the turn) are of magnitudes (0.000 thru 0.007), which are comparable to RRF values calculated from at-sea data that was collected during an earlier phase of the Waterway Performance Study.[12] The fact that the turn region resulted in a substantially larger RRF (0.036) for the RA piloting is somewhat surprising. The particular scenario used for this assessment (Scenario E3) had a visibility of 0.25 nm, which allowed the pilot to visually acquire all the buoys within the turn while he was executing the turn. Under such visibility, it was anticipated that the pilot would shift to the more familiar visual piloting in order to negotiate the turn. However, this finding appears to indicate that either they did not shift to visual piloting, or they did shift and were distracted as they attempted to cognitively time-share between the display and visual piloting. Additional training may help to alleviate this particular problem.

3.2.2 Bias Error

There are differences in performance as a function of bias error (see Tables F-4, F-5, and F-6.) The smaller bias, 16 meters, resulted in better performance than the larger bias of 32 meters. The larger bias was especially troublesome in the crosscurrent of Leg 2. This finding implies that bias errors would interfere with the application of radionavigation as an electronic range when the possibility of crosscurrent was present. Unfortunately, this latter situation is when a range would be most helpful.

The poorer performance with the larger bias error is also apparent in comparison with the visual piloting baseline. (See Tables F-7, F-8 and F-9). The smaller, 16-meter bias shows advantages over visual piloting in a number of regions. The larger, 32-meter bias shows a generally poorer performance than the visual condition. The advantages of an electronic range for trackkeeping are not there.

There is a disadvantage to bias error that is not apparent in the ship control data. The pilots objected to it more than they did the random error. While they were able to compensate (to some extent) for the bias, it should be noted that they do not like to continually do the mental arithmetic required to correct for these biases. They make this point frequently during the debriefing sessions and insist that a device should be able to do the arithmetic for them, "that's what computers are for." In addition, one must question from a cognitive workload perspective the degree to which the time spent performing such arithmetic functions results in less attention being given to other critical piloting tasks.

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[12]Marino, K.L., J.D. Moynehan, and M.W. Smith. Aids to Navigation Principal Findings Report: Implementation As A Test Of The Draft Design Manual. CG-D-04-85 U.S. Coast Guard, Washington, D.C., January 1985.

3.3 DEVICE CHARACTERISTICS

All RA devices resulted in performance that was considered better than Visual Piloting in the Recovery and Trackkeeping Regions. (See Tables F-13, F-14, and F-15). The reader should note that the majority of the statistically significant performance improvements for the RA devices occurred within the Recovery and Trackkeeping regions associated with the second leg. This is the leg which required ownship to have a significant crab angle relative to the direction of travel (i.e., channel centerline). This crab angle was the effect of a crosschannel current component. Previous research has indicated that during the visual piloting process in narrow buoyed channels, pilots rely heavily on the ship's bow and jackstaff to determine proper ownship course[13,14]. When a significant crosscurrent is present, the resulting crab angle severely hampers this type of use of the bow. Apparently, the RA devices, all of which had digital crosschannel information, allowed the pilot to accurately determine his crosschannel position in order to effectively maintain his trackline at the instructed location (i.e., channel centerline).

Device A and Device B resulted in statistically better turn performance (under 0.25 nm visibility conditions) than Visual Piloting. (See Tables F-13 and F-14). This better turn performance may have been a result of the better crosschannel information, which was available to the pilot when Device A or Device B were present to supplement the available visual cues. This better crosschannel information may have allowed the pilots to more quickly return to the channel centerline during the later stages of the turn. This interpretation appears consistent with the better RA device performance in the Recovery and Trackkeeping Regions as discussed in the previous paragraph.

Although Device C resulted in significantly poorer turn performance (under the 0.25 nm visibility condition) than the Visual Piloting, this result should be tempered by several factors.(See Table F-15 for results). First, no radar was available to the test subjects during the experiment. The purpose of this was to force the pilots to use the RA devices. Since Device C does not have a graphic/geographic presentation itself, its performance may have benefited from the availability of radar more than the other devices. Pilots have a certain degree of experience in using graphic/geographic presentation (i.e., radar navigation/radar piloting) to execute course changing maneuvers. Along this same line of thinking, the

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[13] Smith, M.W., K.L. Marino, and J. Multer <u>Short Range Aids to Navigation Systems Design Manual for Restricted Waterways.</u> CG-D-18-85, United States Coast Guard, Washington, D.C. 20593, June 1985. (NTIS AD-A158213)

[14] Smith, M.W., and W.R. Bertsche <u>Aids to Navigation Principal Findings Report on the Channel Width Experiment.</u> CG-D-54-82 United States Coast Guard, Washington, D.C. 20593, December 1981. (NTIS AD-A111337).

maneuver from one electronic range line to another electronic range line is generally recognized as a task, which requires a certain amount of training.[15] Presumably Device C would require the most training because it is the one device that (by itself) does not have a somewhat familiar graphic/geographic presentation. Since the opportunity to provide training on the devices was limited and a radar, which would normally be available at-sea, was not present, the prudent reader should temper his interpretation of this result, which appears initially to be critical of Device C.

3.4 VISIBILITY

When visibility is reduced from 0.25 nm to 0.0 nm, performance in Recovery and Trackkeeping Regions do not change significantly; however, performance in the turns degrades substantially. (See Tables F-16, F-17, and F-18). Reducing visibility from 0.25 nm to 0.0 nm, eliminates two categories of visual cues. First, on the straight legs, it eliminates the visual acquisition of buoys as they pass abeam, which provide reassurance to the pilot that his RA device is in fact working properly. Second, it eliminates the visual acquisition of buoys within the turn, which allows the pilot to accomplish the successful completion of the turn using his normal visual processes if he is so inclined.

The visual acquisition of buoys abeam probably would only significantly impact performance within the straight leg if the magnitude of the bias error was unknown or subject to substantial change during the transit. This is not normally the case with systems like LORAN-C. It may become a problem with GPS if the satellites used to determine ship's position are shifted during a transit.

Loss of visual acquisition of buoys in a turn could have significant impact on performance if (a) visual piloting processes dominate the normal turn navigation procedure and (b) the pilot had inadequate training in the potential back-up procedures. This may be the case here, since the normal back-up procedure, radar navigation/radar piloting, was not available. On the other hand, it should be noted to consider radar piloting as a "back-up technique" for negotiating a turn under zero visibility conditions may be inappropriate. Pilots generally use radar piloting to negotiate turns within such restricted channels only under "emergency" conditions (i.e., a fog bank temporarily obscures all buoys within the turn). It may be more appropriate to say that when the visibility obscured all visual cues in the turn, the pilot was left with only his mental dead-reckoning skills. This would be a less than desirable situation even if the radar had been available.

As a result, in order to successfully implement an all-weather navigation system, it would appear that one important "acid" test is how well it allows pilots to handle ownship within the turn under zero visibility conditions.

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[15] Hammell, T.J, J.W. Gynther, and V.M. Pittsley. Experimental Evaluation of Simulator-Based Training for Marine Pilots. National Maritime Research Center, Kings Point, New York 11024, April 1984.

This brings us to the point of trying to better understand the difficulties encountered during the negotiation of the 35-degree turn in this experiment under zero visibility.

First, it should be noted that many pilots complained during the debriefing session of the poor rate-of-turn information provided by the devices, including Device A, which had an ownship heading vector updating every one (1) second from the "jittering" position of ownship. The general feeling was that standard radar systems provide more accurate rate-of-turn information than was provided by the simulated RA devices. This should be improved in any RA devices developed for future research. In addition, providing a Rate-of-Turn Indicator (ROTI) on the bridge and ensuring that the pilot has necessary training to use it for constant radius turns should also be considered. The Dutch pilots in Rotterdam have had substantial success using a ROTI with their Decca Brown Box system.[16]

Second, further analysis reveals that a critical problem, for those pilots who had the most difficulty with the turn under zero visibility, was initiating the turn too late. This is illustrated in Figure 3-1. All pilots were initially ranked according to their crosstrack position upon their completion of the turn pullout. The further away from the centerline, the lower their relative ranking. The alongtrack distance (ATD) and the crosstrack distance (XTD) of each pilot's position at turn initiation was then established. (Note: ATD is measured from the intersection of the two channel centerlines while XTD is measured from the centerline of the relevant channel). This simple tabular analysis clearly indicates the penalty of initiating the turn late, namely substantial deviation from centerline at turn pullout.

The reader may be interested to note that the Spearman Rank Correlation Coefficient (r_s) between the Pullout XTD and the Initiation ATD was 0.74. If one assumes for a moment that a similar correlation coefficient (r_s=0.74) could still be obtained given two more samples (which would make N=10), a statistical test of the null hypothesis, namely that these two variables are not related, could be accomplished according to procedures advanced by Kendall.[17] The null hypothesis could then be rejected at an alpha-level of 0.10 (one-tailed).

The fact that some pilots were late in executing the turn may be an indication of a need for (a) additional training in using the ATD information presented on the display or (b) improved display design to highlight this information. It should be noted that during the debriefing sessions, the majority of pilots indicated that they really focused on the digital XTD information. No pilots reported focusing on the digital ATD

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[16]Hussem, J., C. DeBoer, and P.J. Paymans. "Seven Years Experience with Simulator Training of VLCC Pilots in the Netherlands, "Proceedings of the Second International Conference on Marine Simulation". Computer Aided Operations Research Facility, Kings Point, New York, June 1981.

[17]Siegel, S. Nonparametric Statistics for Behavioral Sciences, McGraw-Hill Book Company, Inc., New York, 1956.

Decreasing Turn Performance

RESULT

Pilot Rank at Turn Pullout (DL3)

Pilot	XTD (ft)
815	16
867	27
876	29
884	141
859	170
872	208
849	235
838	259

TURN INITIATION

Ownship Position at Time Turn Initiation

ATD (nm)	XTD (ft)	
0.156	28	NORMAL INITIATION
0.138	69	
0.135	34	
0.137	79	
0.139	11	
0.000	-56	LATE INITIATION
0.062	8	
0.077	-9	

Figure 3-1: Correlation between Turn Pullout Performance and Turn Initiation Under Zero Visibility Conditions ....Scenario 8

information. Use of the XTD is intuitive and its accuracy could be easily verified whenever channel buoys passed abeam. Use of the ATD, on the other hand, requires more understanding and its accuracy would not normally be verified during the familiarization and experiment scenarios.

3.5 SUMMARY

This section of the report attempts to provide an overview of the experimental findings. The reader should review the discussions associated with each finding in the proceeding sections in order to fully understand the context in which each statement is made.

(1) Higher random error (18 meters versus 10 meters 2 drms) resulted in greater ownship track variability and hence greater risk.

(2) Use of a RA device, with an error of less than 10 meters (2 drms), resulted in improved performance over Visual Piloting.

(3) RA navigation performance with the largest random error (18 meters 2 drms) resulted in poorer performance then the Visual Piloting, especially in the critical turn region.

(4) There were differences in performance as a function of bias error, with 16 meters resulting in better performance than 32 meters.

(5) The larger, 32-meters bias error resulted in generally poorer performance than Visual Piloting.

(6) All RA devices resulted in performance better than Visual Piloting in the Recovery and Trackkeeping Regions.

(7) Device A and Device B resulted in statistically better turn performance (under the 0.25 nm visibility condition) than Visual Piloting.

(8) Device C resulted in significantly poorer turn performance (under the 0.25 nm visibility condition) than the Visual Piloting.

(9) When visibility was reduced from 0.25 nm to 0.0 nm, performance in Recovery and Trackkeeping Regions did change significantly; however, performance in the turns degraded substantially.

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Section 4

CONCLUSIONS

4.1 SYSTEM ACCURACY, VISIBILITY, AND SHIPHANDLING REQUIREMENTS

4.1.1 System Accuracy: Random Error

The primary objective of the experiment was the evaluation of the requirement in the 1986 Federal Radionavigation Plan for an 8-20 meter (2 drms) system accuracy goal for larger vessels in the harbor and harbor approach phases of navigation. The results of this experiment indicate that this is a very appropriate goal. To support this conclusion, Figure 4-1 presents a sample of relevant results. It summarizes performance at two levels of random error and for the visual baseline condition included in the experiment. Performance is indexed by the Relative Risk Factor (RRF) and plotted for each of the three shiphandling tasks required by the experimental transit: turn, recovery, and trackkeeping. (The RRF measure is described in Section 2.10.3; the shiphandling requirements are described in Appendix C, "Instructions to the Pilot.")

Radionavigation performance with the 8-20 meters (2 drms) spectrum of accuracy approximates visual piloting performance for an exactly comparable transit. Note that the degree of approximation depends on the shiphandling task considered. For the recovery to the centerline of the channel after a turn, the entire spectrum evaluated even provides an advantage over visual piloting. Performance in the turns is most susceptible to an increase in random signal error. If turns are a consideration, RA system accuracy at the lower end of the spectrum is required for the 30,000 dwt tanker in a 500-foot channel for performance comparable to visual. This is true even when the visibility is such that the pilot can visually acquire all buoys within the turn (i.e., 0.25 mn visibility). During the exercises, the pilots apparently had difficulty effectively shifting between radio aid navigation in the straight legs and visual piloting in the turns, and increased random error further increased the difficulty.

4.1.2 System Accuracy: Bias Error

Effective compensation for known, but uncorrected bias error, did not appear to be particularly troublesome for pilots, as long as the position displayed for ownship was still within the boundaries of the channel. Pilots appeared to be able to mentally accomplish the necessary mathematics to successfully navigate ownship, although they strongly objected, and rightly so, to this increase in their mental workload. From a cognitive processing perspective, one must question the degree to which the time spent performing such mathematical activities results in less attention being given to other critical piloting tasks. In addition, given the micro-processors available today, it would appear possible to have pilots simply dial in a correction for the known bias error and let the device continually apply the necessary correction. Finally, any display of the position for ownship with the uncorrected bias outside the boundaries of the channel was unacceptable to pilots. Their reaction would have been either to stay at the dock or go to anchor.

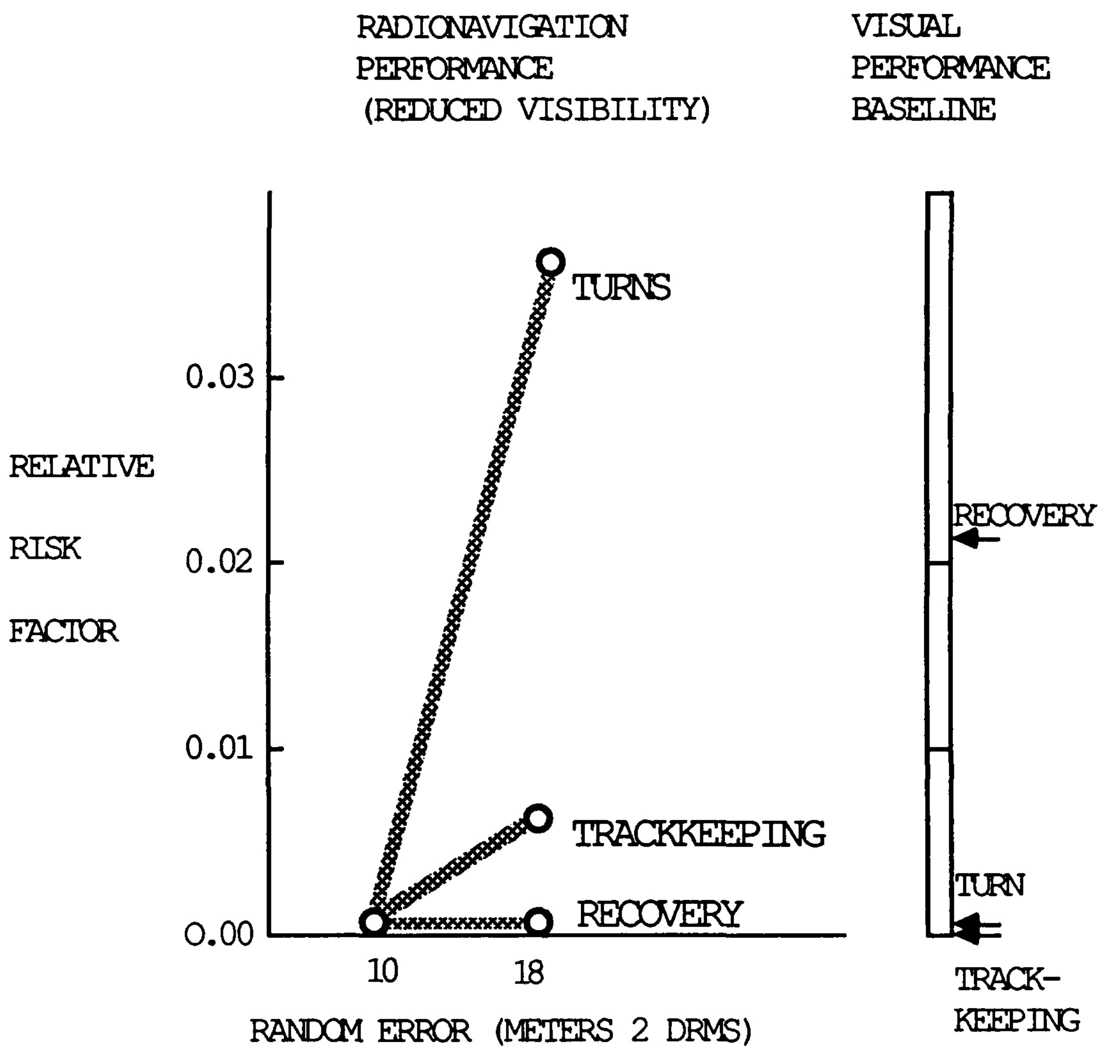

FIGURE 4-1: RADIONAVIGATION SYSTEM ACCURACY AND PILOTING PERFORMANCE (30,000 dwt Tanker, 500-foot Channel)

4.1.3 Visibility

RA systems with 8-20 meter (2 drms) accuracy enhanced the safety of navigation under reduced visibility conditions down to 0.25 nm visibility. This was particularly true in the trackkeeping and recovery regions of the channel, for the types of devices/displays investigated. In fact, even under zero visibility conditions, piloting performance with the RA devices was better in these region than that observed for visual piloting. However, this experiment clearly documents the "Turn Region" as a major stumbling block to the use of these types of devices as "all-weather" navigation systems. Both close analysis of the data and pilot reactions suggested that poor rate-of-turn information is probably the cause for this difficulty. Future experiments should investigate the use of displays which better depict desired and actual vessel rate-of-turn information within the turn region.

A second concern, regarding these devices under "all-weather" conditions, is the maintenance of the proper level of vigilance given to other traffic vessels within the channel. If the position of traffic vessels is not displayed on the RA device, the pilot still must go to the radar to monitor traffic vessel motion. This could be cumbersome, if the pilot is required to time-share between two similar, but different, graphic plan-view displays.

4.2 DEVICE CHARACTERISTICS AND SHIPHANDLING REQUIREMENTS

4.2.1 Recovery and Trackkeeping

The results of this experiment indicate that a variety of RA devices can effectively support navigation within the trackkeeping and recovery regions. The important feature appears to be an easily-usable digital readout of ownship's position relative to the channel centerline. The majority of pilots indicated that this was the information on which they really focused when navigating within the straight legs of a particular channel. All three device evaluated during this experiment (see Section 2.4) had such digital cross-channel position read-outs.

4.2.2 Turn Region

The RA devices investigated did not adequately support navigation within the turn region of restricted channels. The graphical devices investigated (i.e., Devices A and B discussed in Section 2.4) did have the potential to allow pilots to adequately time-share between radionavigation and visual piloting techniques when visibility was such that turn region buoys were visually available. However, these graphical presentations did not satisfactorily support safe navigation when all visual contact with turn region buoys was lost (i.e. zero visibility/all-weather navigation). As noted in Section 3.4 and 4.2.1, improved rate-of-turn information appears to be the primary candidate for correcting this problem.

4.3 POTENTIAL OPERATIONAL USES

4.3.1 General

The successful use of precision radio aid systems for restricted channel navigation is no longer a futuristic vision. Such radio aid systems are available today. The results of this experiment support such use. However, it is important to understand the conditions and limitations of the use of radio aids within the restricted waters navigation setting. In order to understand these conditions and limitations, it is appropriate to identify and discuss three distinct operational uses of radio aids: a) electronic ranges, b) reduced visibility enhancements, and c) an all-weather navigation system. Figure 4-2 summarizes the requirements of these operational uses and their support in the experimental findings.

4.3.2 Electronic Ranges and Reduced Visibility Enhancements

The experimental results support the near-term implementation of radio aids as electronic ranges. This would provide the pilot with another source of navigational information, which if properly implemented would be highly accurate and highly reliable under all weather conditions. Such electronic ranges would be particularly useful in situations when ice forces the removal of aids, or when a few users require additional, more accurate navigational information. There may be difficulties in getting commercial operators to install such devices on their vessels; however, such an approach would respond to current pressures for passing on costs to the end user.

The experimental results support the near-term implementation of a variety of radio aid systems as reduced visibility enhancements down to visibilities as low as 0.25 nm, or to those just allowing intermittent view of the aids. All potential operators should be aware of the limitations of the current devices when (a) encountering traffic vessels or (b) negotiating turns under visibilities less than 0.25 nm. In addition, operators should use additional caution when the accuracy or the radio aid system in a particular geographic area approaches the upper end of the 8-20 meter (2 drms) spectrum.

4.3.3 All-Weather Navigation

The experimental results do not support the use of the types of radio aid systems evaluated during this experiment as a principal means of navigation under zero visibility conditions. The primary concerns focus on the need for (a) additional research into the role of an RA device in negotiating turns under zero visibility conditions and (b) additional insight into the minimum training requirements for using such devices.

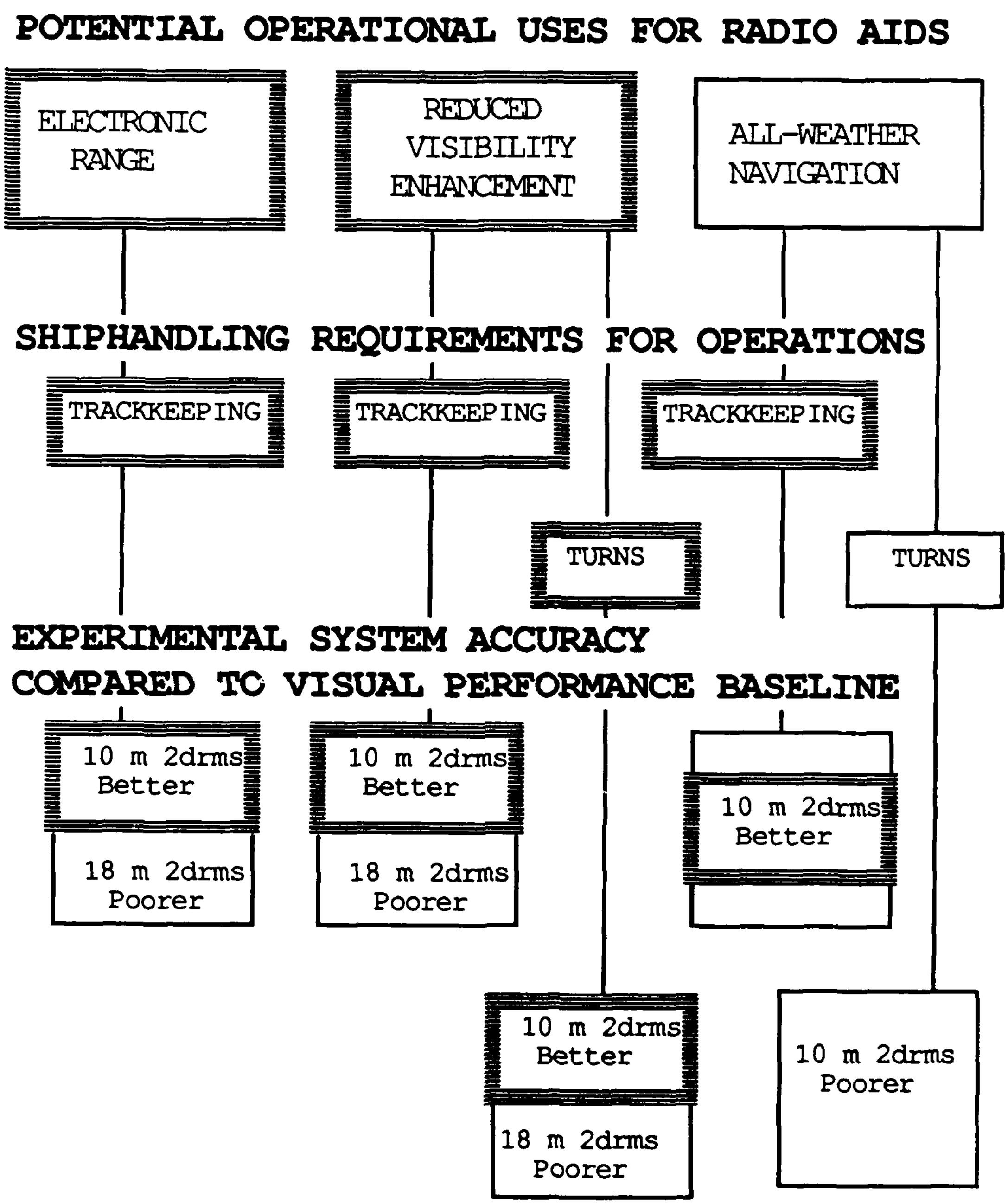

FIGURE 4-2: POTENTIAL OPERATIONAL USES AND THEIR EXPERIMENTAL SUPPORT (Shaded boxes describe support for near-term implementation.)

4.4 RECOMMENDATIONS FOR ADDITIONAL RESEARCH

4.4.1 Radar Navigation Baseline

Data on piloting performance with radar should be documented for a number of conditions, including reduced visibility (0.25 nm) and zero visibility (0.00 nm). Visual piloting performance has been used in this experiment, and in its subsequent analysis, as the acceptable-risk goal for the RA systems. While this may be appropriate, the radar is the present navigation tool upon which pilots rely most heavily as visibility decreases. In other words, radar may be the real competition of these prototype RA devices. The impetus for pilots to use an RA device would be improved if it could be demonstrated that such a device would significantly enhance their piloting performance over what they could attain with radar alone.

4.4.2 Device C with Radar

Device C (digital information only) should be re-evaluated with a radar available on the bridge. Device C was the only device that did not have a birds-eye graphic display. This type of presentation would normally be available to the pilot on all large merchant vessels in the form of a radar. The elimination of radar from the experiment in order to force the pilots to use the RA devices was an appropriate procedure. However, it may have also penalized the digital-only display more than the other RA displays, which had graphic presentations similar to radar.

4.4.3 Turns Under Zero Visibility

Additional research should be conducted on the role of an RA device in negotiating turns under zero visibility conditions. This investigation should also address the capabilities of radar and a rate-of-turn indicator (ROTI) to provide important informational cues to the pilot on ownship's yaw rate. As previously noted, Netherland pilots have been very successful in using their digital Decca Brown Box with a ROTI to effectively navigate the approach channels to Rotterdam.

4.4.4 Minimum Training Requirements

Additional insight should be gained into the minimum training requirements for personnel using RA devices aboard large vessels within restricted channels. The experience gained during this experiment appears to point towards the importance of sufficient, proper training to ensure the safe navigation of ownship, via an RA device, within restricted channels. The specific objectives and structure of such training should be better defined. In addition, as RA devices are perfected and their use becomes more and more prevalent, particularly under limited visibility conditions, the possible role of an RA systems certification/license endorsement should be further investigated.

Appendix A

Overview of Ship Control and Navigation Training System (SCANTS)

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APPENDIX A

THE UNITED STATES COAST GUARD ACADEMY SIMULATOR

A.1 INTRODUCTION TO SCANTS

SCANTS, the Ship Control and Navigation Training System, was purchased by the U.S. Coast Guard in the mid-1980s at a cost of approximately 3.4 million dollars. Originally intended as a training tool for U.S.C.G. cadets, the system was installed at the Coast Guard Academy in 1985, and has been used effectively for research as well as for various types of training. Ship Analytics provided the computers and software to drive the system and currently provides ongoing support and maintenance. Cadet training uses SCANTS, in concert with radar and navigation laboratory classes and on-the-water training, to teach rules of the road and to prepare cadets to function as Officers of the Deck. The Coast Guard now also makes use of SCANTS in classes given to train prospective commanding officers and prospective executive officers (PCO/PXO).

A.2 THE SCANTS FACILITY

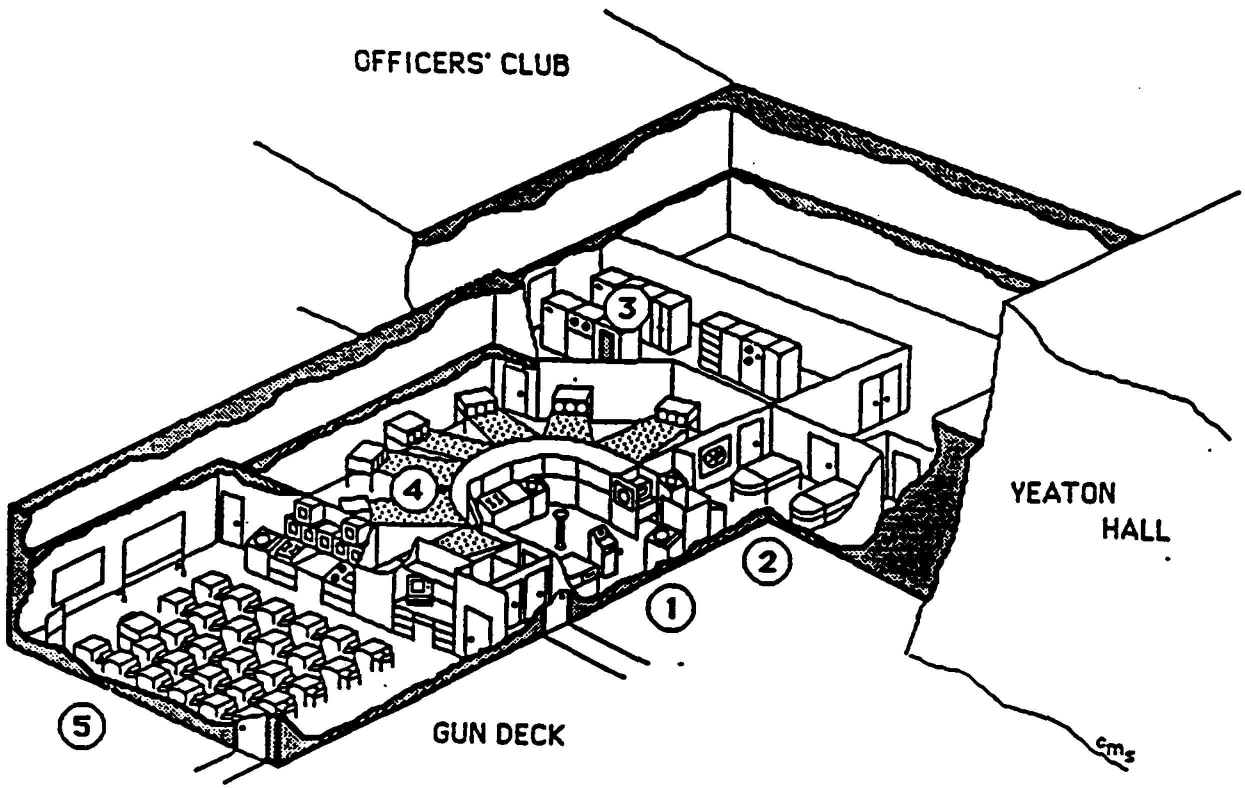
The SCANTS facility includes a full-size mock-up of a ship's bridge and combat information center (CIC), as illustrated in Figure A-1. The visual scene on the bridge consists of computer-generated color images rear-projected on seven screens, providing a 182-degree horizontal field of view. Training at the Academy uses an ownship simulation of a 270- or a 378-foot Coast Guard cutter. However, other Ship Analytics ship models can be installed as ownships. Sophisticated ship hydrodynamic models provide realistic handling characteristics for the specific ship in use. This, along with a number of other capabilities, serves to make the simulation quite realistic. Environmental conditions such as wind, current, and height of tide, and bank or passing ship suction and cushion are simulated. Their effects on the ownship are apparent in the visual scene and in the bridge instrumentation (anemometer, fathometer, LORAN C etc.) displays. Other bridge instrumentation includes working radios (generally used to simulate communication with traffic ships and other ship personnel), engine order telegraph (EOT), steering stand, pelorus, sound signal equipment, and two radar units.

Other components of the system are:

- Computer hardware including one Digital VAX 11/750, two VAX 11/780's, seven Adage image processing units, and an LSI 11/23 ADAC input/output processor located in a computer room adjacent to the CIC.

- Image projection instrumentation, consisting of seven RGB rear screen projectors capable of providing day or night color scenes, located in a projection room adjacent to the bridge. The original Barco-vision projectors were recently replaced with Sony projectors to improve the quality of the visual scene.

U.S. Coast Guard Academy
Ship Control and Navigation Training System
(SCANTS)



Conceptual view looking South from Hamilton Hall

1. Bridge: life-size, complete with steering stand, engine order telegraph, pelorus, communications and 2 radar indicators
2. Combat Information Center with full communications, 2 radar indicators, plotting and surface summary plot tables
3. Computer Room: 1 VAX 11/750, 2 VAX 11/780's, 7 Adage image processing units, ADAC input/output processor
4. Projector Room with 7 SONY rear screen projectors providing a 182° color day and night wrap-around visual display
5. 30 person briefing theater with graphic feedback display, remote monitoring station and instructor/ operator station

- Briefing theater with graphic feedback display which allows viewing of ownship and traffic ship tracks after the simulation has ended.

- Remote monitoring station consisting of closed circuit television displays showing the bridge and CIC, and five CRT monitors duplicating the scene on the middle five screens on the bridge.

- Three instructor/operator stations which allow operation of the simulator from the remote monitoring station, the briefing theater, or a room between the bridge and CIC.

A.3 USE OF THE SIMULATOR IN RESEARCH

SCANTS and other similar systems such as the Maritime Training and Research Center (MTRC) in Toledo, Ohio, are valuable as research tools. Both of the aforementioned systems have been used in the Waterway Performance Design and Evaluation Study conducted by Ship Analytics for the U.S. Coast Guard Office of Engineering and Development. Issues addressed in the study have included the evaluation of aids to navigation (their arrangement, position, proximity to land, etc.), the effectiveness of radio aids to navigation, and the effect of ship maneuverability on performance in a waterway.

All phases of the Waterway Study have been concerned with navigation in restricted waters. A ship's bridge simulator such as the SCANTS facility is well-suited for this type of research because it can be used to simulate an actual or theoretical waterway. For instance, in one experiment local commercial pilots were allowed to familiarize themselves with the simulator by making trial runs into Providence, R.I., a waterway with which they were very familiar. Later, the data base was changed and they were asked to navigate in an unfamiliar waterway. The realism of the simulation greatly affected the pilot's acceptance of the simulator and facilitated the research.

In simulator experiments conducted for the Waterway Study, a participating pilot is briefed about the experiment and given a chart of the experimental waterway in the briefing theater (see figure). The pilot is provided with a helmsman and is instructed to operate the ship as he normally would from the bridge. The visual scene used for experimentation may contain a landmass and aids or the aids alone, to meet the objectives of the experiment. The experimenter observes the pilot either from the bridge or from the remote monitoring station where the pilot's orders to the helmsman are recorded. Data are collected by a computer during the simulation. These data are examined in a short form following the run, and more extensively later. Pilots are normally given no feedback about the run they have just made, although this is another area of performance that could be investigated. Research conducted using SCANTS (and MTRC) has yielded significant information and has resulted in valuable procedures allowing the Coast Guard to evaluate the risk associated with ships entering restricted waters.

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Appendix B

Instructions to the Pilot

Day 1: Familiarization

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APPENDIX B

RADIO AIDS EXPERIMENT PILOT BRIEFING

INTRODUCTION

The present experiment is designed to evaluate the effectiveness of several types of radionavigation devices for piloting a ship in a narrow channel. Positioning errors have been included in this evaluation in order to determine the effect of system error. This determination is necessary for specifying the system accuracy requirements for radionavigation. In some transits visibility will be limited so that we can examine the tradeoffs among device characteristics, positioning error, and visibility.

The experiment will be run in two days. Day 1 is designed to familiarize you with the simulator, the response characteristics of the ship, the radio aid devices, and the range of position accuracies that can be expected from these devices.

Day 2, the experimental day, will be run as soon after Day 1 as your schedule permits. The radio aids devices will be identical on both days but the transits will be made in different channels. Like Day 1, some transits will be made under conditions of reduced visibility.

QUESTIONS FOR THE START OF DAY 1

1. Have you ever before "piloted" a simulator? Which one? What type of exercise? What did you think of the simulator and the exercise?

2. Please describe briefly your practices for piloting in very limited visibility. What do you consider an unsafe or unacceptable visibility?

   In limited visibility what equipment or techniques do you use? Have you ever used an electronic navigational aid (electronic chart, "smart" LORAN, etc.) as a supplement for piloting in a narrow channel in limited visibility? What type of aid? How did you use it?

3. Do you routinely bring ships into Providence? In unlimited visibility are there particular natural features or cultural objects you find essential to your transits? Please describe these features or objects.

   In limited visibility are there characteristics of Providence that are essential to your transit? Are there bank effects or currents that are characteristics of Providence? Please describe these characteristics. Are the bank effects helpful in limited visibility? What speed do you typically use in limited visibility?

RADIO AID DEVICES

You will be using 3 different radio aid devices, each with differing capabilities. Figure B-1 shows the essential features of the three devices.

DEVICE A

Device A graphically presents position information on a plan-view display, showing a section of the waterway positioned track-up on the screen. The display shows landmass, buoys, major aids, the channel outline and the ship's outline drawn to scale.

Position information is provided digitally as well. Distance to Waypoint is shown in nm. When ownship is within 1 nm of the waypoint, the Distance to Waypoint will be shown in feet. The waypoint is a point is a point in the center of each turn. Distance to Centerline is shown in feet to the right or left of the channel centerline, and its direction is indicated by arrows. An indicator reading of [--> 30 ft] would mean that ownship needs to move 30 feet to the right to be on the centerline. Similarly an indicator reading of [<--20 ft] would mean that ownship needs to move 20 feet to the left to be on the centerline.

Range is selectable to a 0.5 nm, 1.0 nm, 1.0 nm, 1.5 nm, or 3 nm scale. You may change the scale of the display at any time by touching the desired touch-sensitive square (0.5 nm, 1.0 nm, 1.5 nm, and 3.0 nm). The square you select will light and the plan view will be redrawn to the desired scale. Touching the Reset PPI Display square located on the device will automatically reset ownship to the lower quarter section of the screen. The device will also reset when ownship is approximately 1200 feet passed a waypoint and when the ship is 3/4 of the way up the screen.

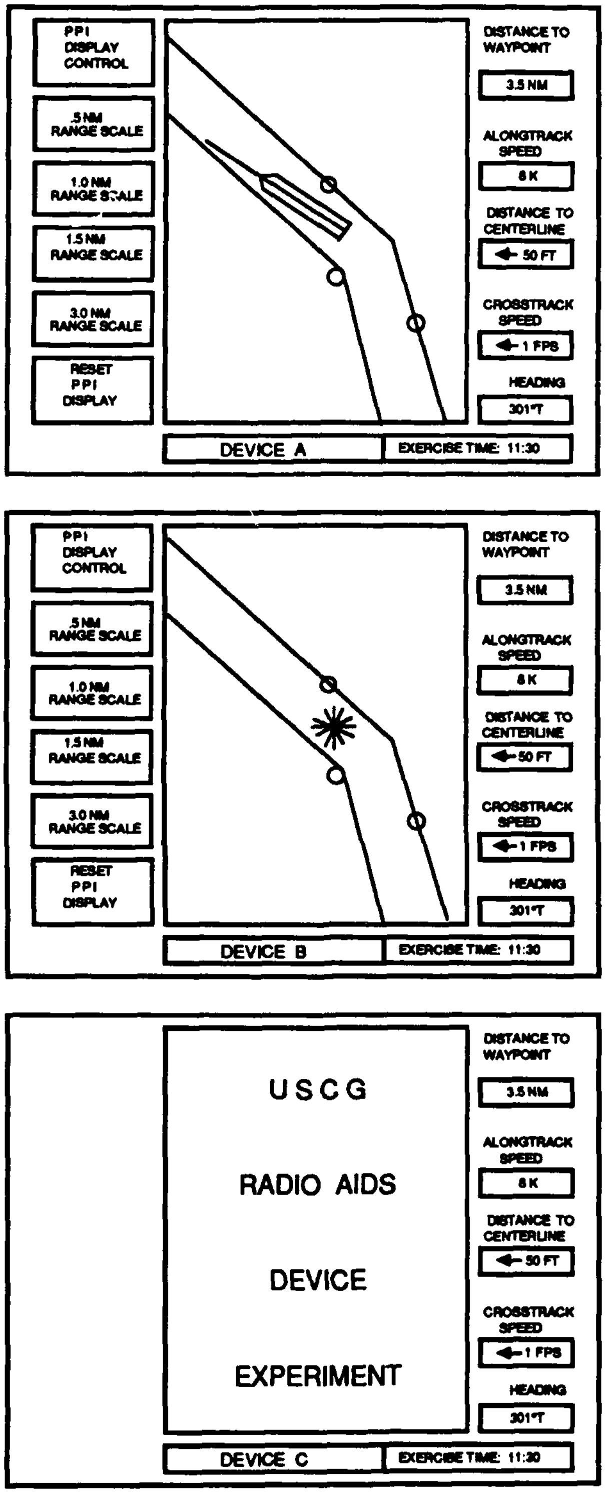
Motion is provided by the ship's movement up the channel in true motion.

Speed over ground both alongtrack and crosstrack, is provided digitally. Alongtrack Speed is shown in knots. Crosstrack Speed is shown in feet per sec. in the direction that ownship is moving and is indicated by arrows. A crosstrack speed indicator reading of [<--2 fps] means that ownship is moving leftward at 2 fps.

Heading information is provided by the aspect of the ship in the channel, by a heading flash, and by a digital readout.

DEVICE B

Device B is similar to an electronic chart. It differs from Device A in that the waterway is positioned north-up rather than track-up. The graphical information is also considerably less sophisticated. Ship position is indicated by an asterisk; ship aspect and heading flash information have been omitted from this device. Range can be selected as described above. The display can be reset as described above.



Note: Drawings not to scale

Figure B-1: The RA Display Devices

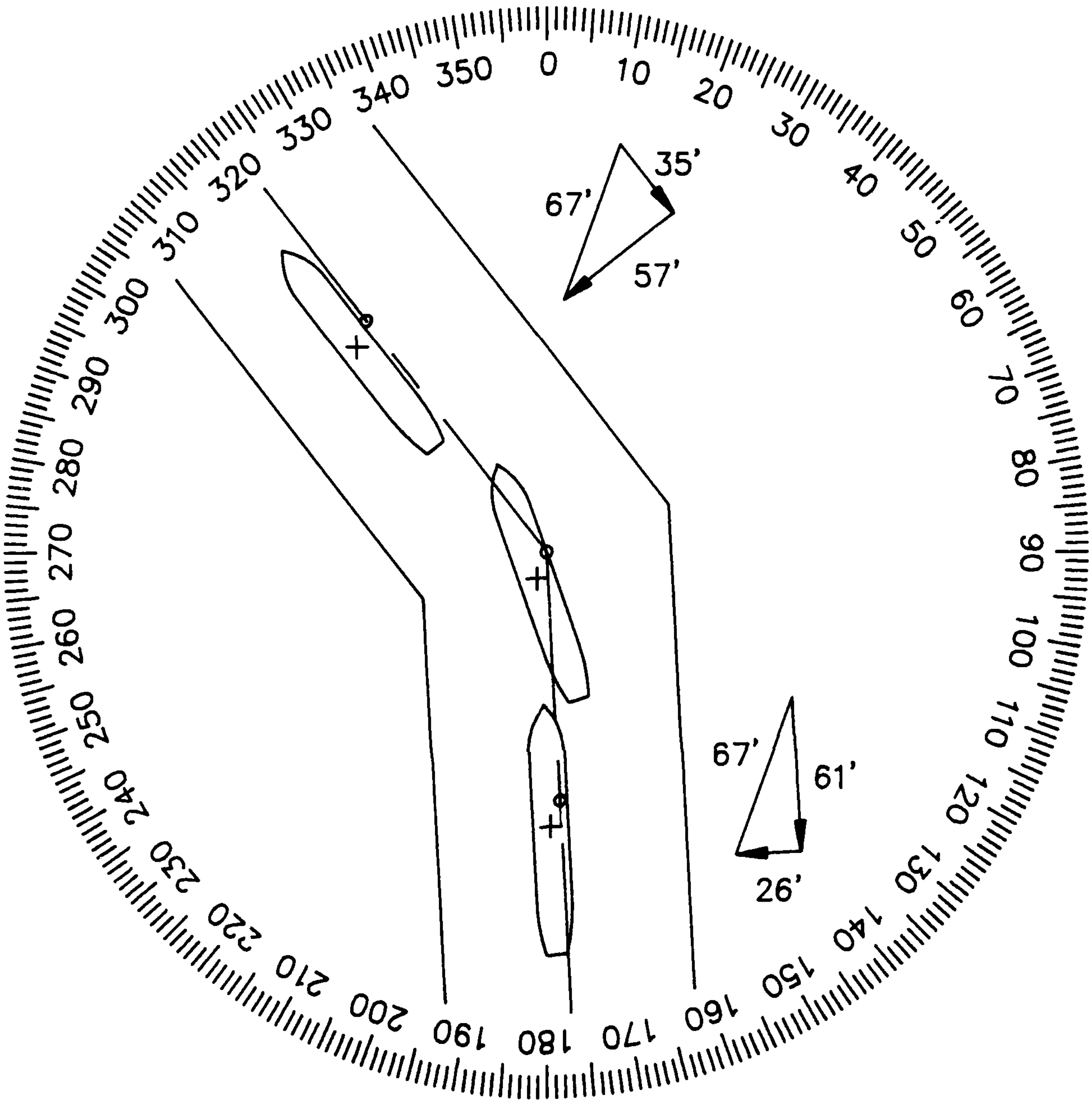
DEVICE C

Device C differs from Devices A and B in that it presents only digital information.

SYSTEM ERROR

Random Error: In some scenarios a random error with a specified standard deviation (SD) will be applied in both the N/S and the E/W directions. This error will appear as "jitter," or variations in position, with each update on the graphical display. It will appear as variations in alongtrack and crosstrack distances on the digital display.

Bias Error: In some scenarios a bias error in the ship's position will also be applied. This error will be a constant distance at a constant bearing. This bias will affect both the graphical and the digital displays. Illustrations of two biases you will see today appear as Figures B-2 and B-3. In each case the displayed position of the ship is always displaced in the direction and for the distance specified from its actual position. In the illustrated cases, try to keep the displayed position to the left and behind the position you actually intended. To help you compensate for the bias in this way, each scenario chartlet will show you the bias in feet for each leg of the transit.

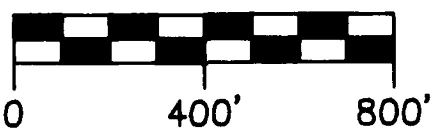


BIAS ERROR 67' TO 200°T

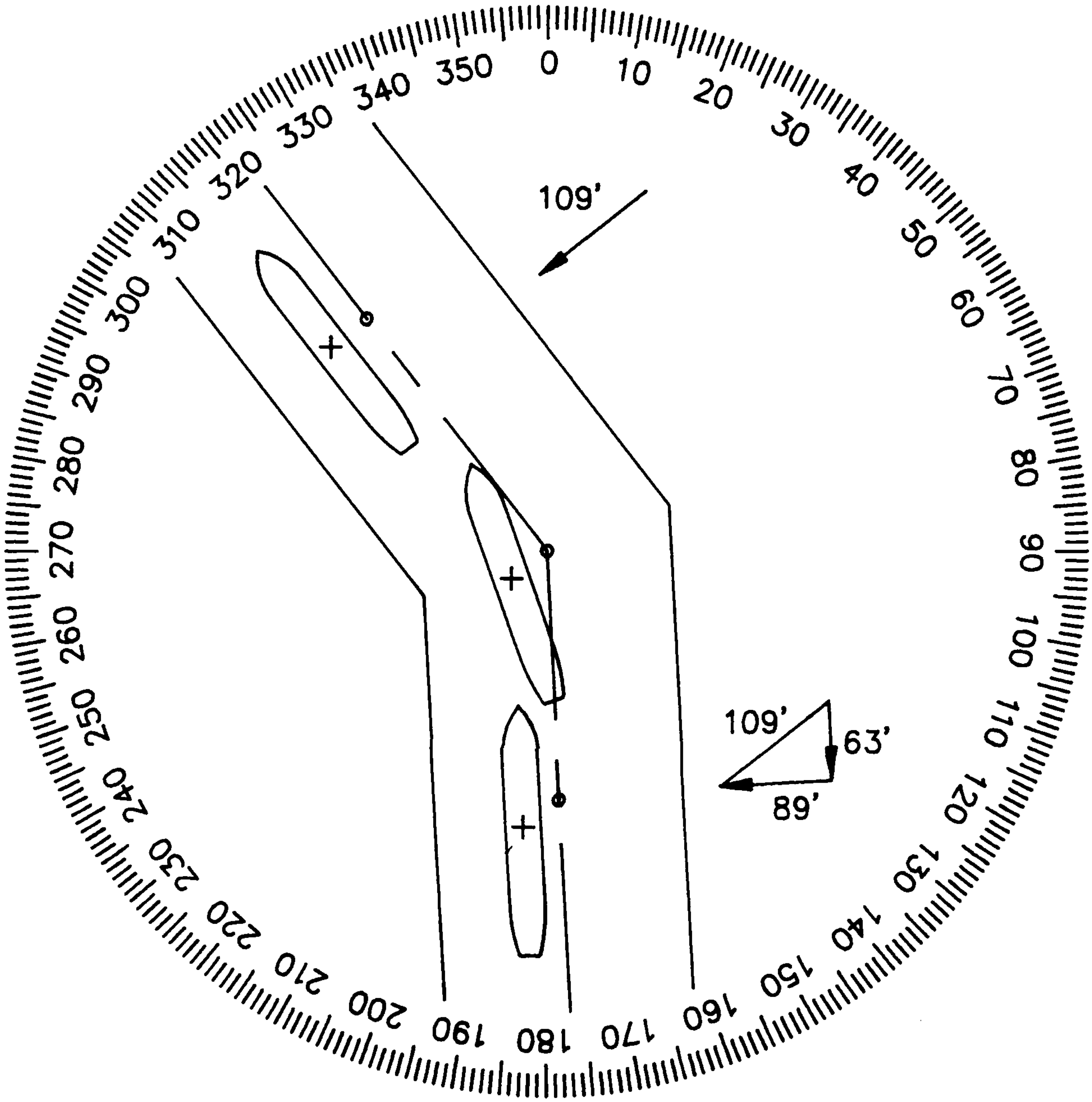
(SCENARIOS P0, P1, P4, P5 AND P6)

o ACTUAL POSITION

+ BIASED POSITION



SCALE: 1":400'



BIAS ERROR 109' TO 232°T

(SCENARIO P8)

o ACTUAL POSITION

+ BIASED POSITION

SCALE: 1": 400'

SHIP PARTICULARS AND BRIDGE LAYOUT

The ship is a 30,000 dwt tanker, that is fully loaded with a draft of 35 feet, a length of 595 feet at the waterline and a beam of 84 feet. Turn circle data is attached as Figure B-4.

The ship has a split house with the bridge 85 feet forward of the center of gravity. The eyepoint is 48 feet above the water. The location of the eyepoint along the ship's axis is illustrated in Figure B-5.

The EOT, RPM, speed equivalents for Tanker Diane are as follows:

EOT	RPM	SPEED (KTS)
DEAD SLOW	11	2.6
SLOW	44	6.6
HALF	68	9.9
FULL	88	12.6

The bridge is laid out like a typical merchant bridge. There will be a helmsman to receive your helm and course orders. Please operate the EOT and please announce your changes.

There will be a gyrocompass repeater with bearing ring, a rudder angle indicator, RPM indicator, speed log (through the water) and ships clock. The preferred viewing location is at the center gyro repeater. Radar will be available only for Scenario PO, the first run.

There will be no traffic in any scenarios.

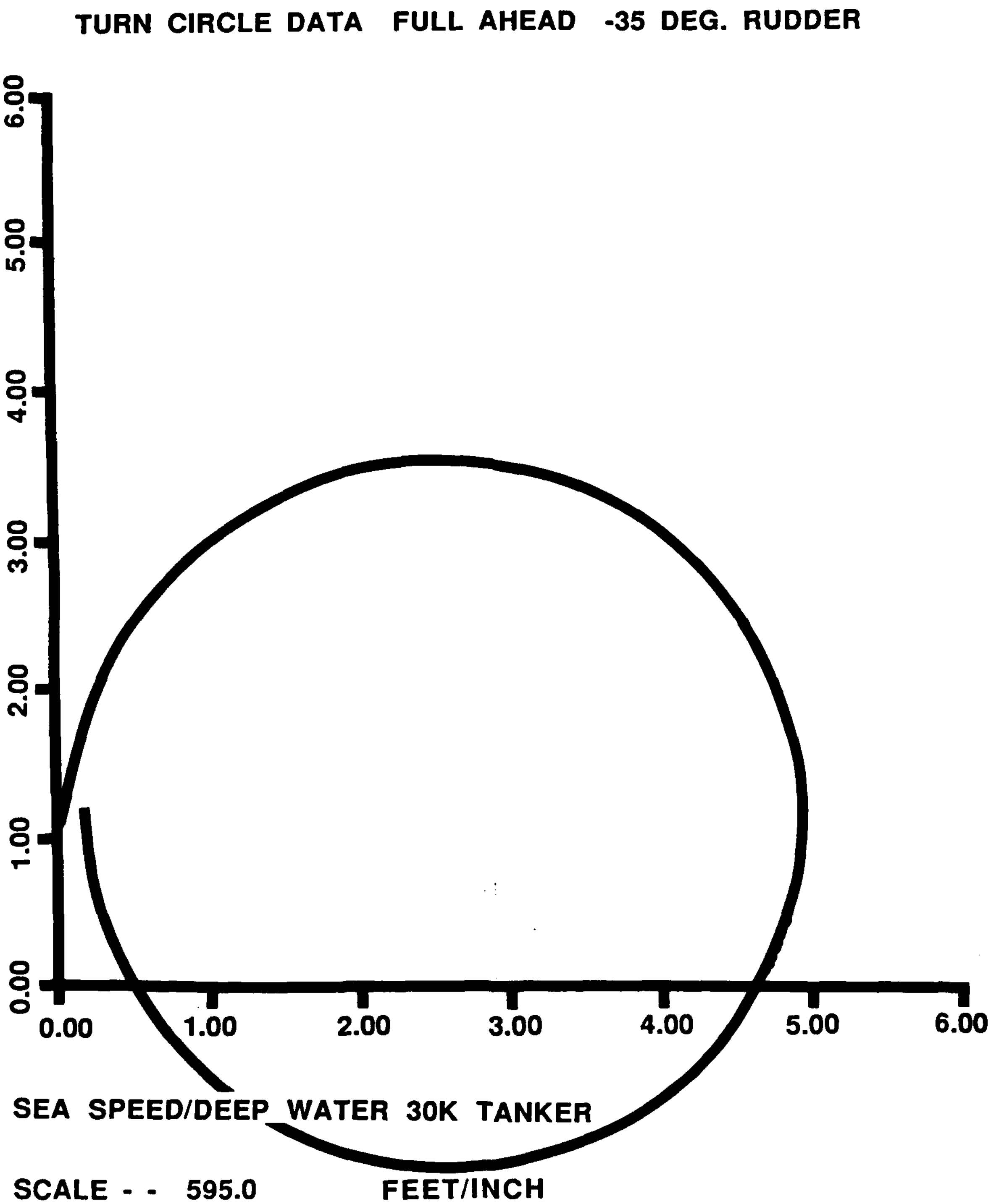


Figure B-4: Deep Water Turning Circle for Tanker Diane

Length - Overall	616 ft
Length - Between Perpendiculars	595 ft
Beam	84 ft
Draft	35 ft
Eyepoint - Above Water	48 ft
Eyepoint - Forward of Center of Gravity	85 ft

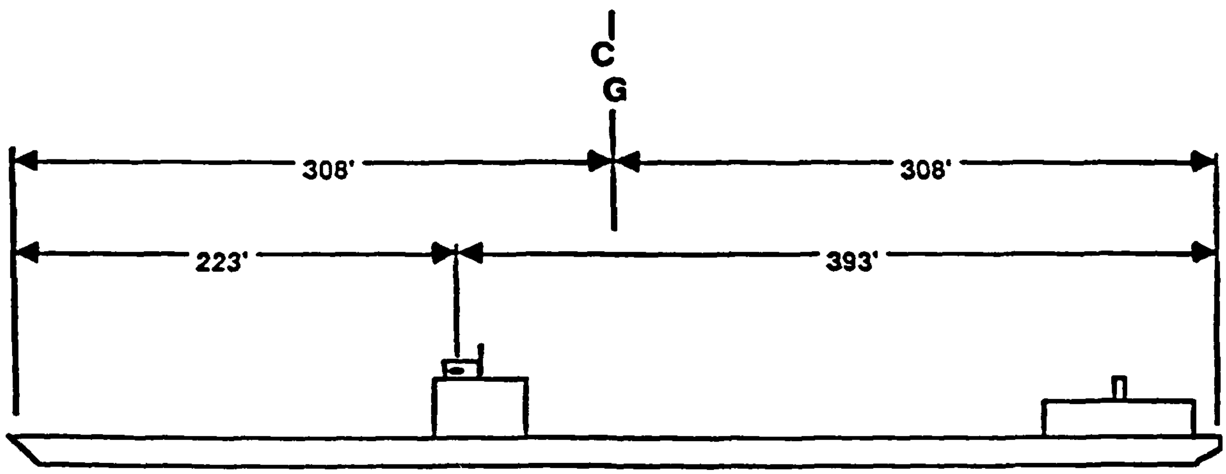


Figure B-5: Physical Characteristics of Tanker Diane

PROVIDENCE CHANNEL FOR DAY 1

We have simulated a simplified version of Providence as a familiarization exercise. A chart of the channel, showing the landmass and the aids, is attached as Figure B-6 (Chartlet PO). There will be no wind, current, or bank effects in the exercises run today.

You will be making multiple runs on this channel for the purposes of familiarizing yourself with the devices and of evaluating device usefulness under a variety of conditions. Table B-1 shows the conditions (visibility, random error, bias error, and device) associated with each run.

PROVIDENCE FAMILIARIZATION SCENARIO PO

Scenario PO is a familiarization scenario. It will start with ownship 82 feet right of the centerline of the channel, approximately 1.1 nm below the turn and with a heading of 353°T, at the point indicated on Chartlet PO. Ownship's speed through the water will be approximately 9.9 knots. Please stay as close to a strictly defined, "centerline" as is practical. As a strict test of the devices' effectiveness, we will ask you to keep the ship on the channel centerline except when making turns. Make the turns as you think appropriate and return to the centerline again as soon as prudent in the next leg. You are free to select the speed you consider appropriate for each leg of the channel. Visibility will be unlimited. Device A will be available to compare the situation on the display with the view "out-the-window" and on the radar. There will be no traffic.

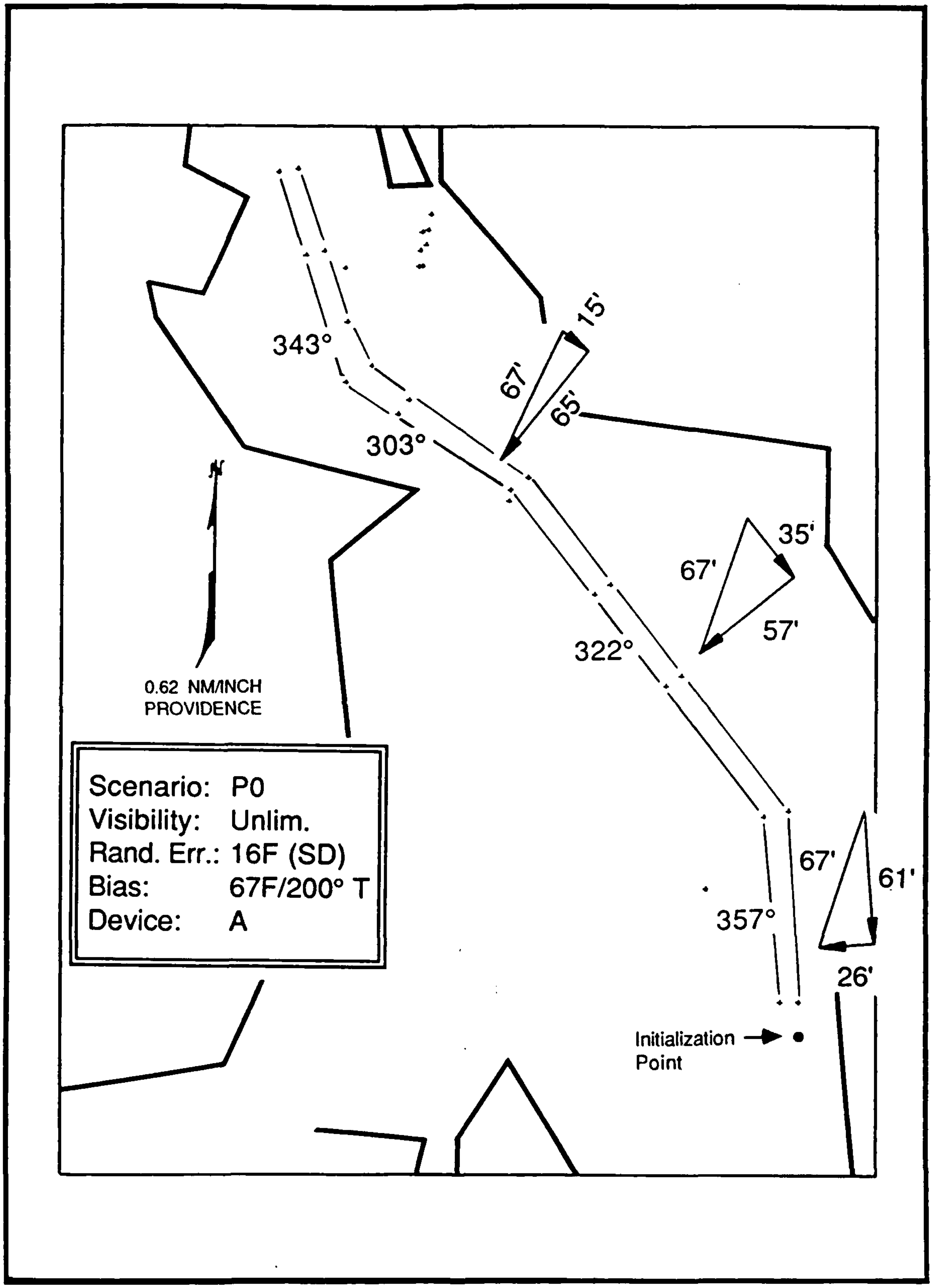


Figure B-6: Simulated Approach Channel to Providence (Chartlet P0)

TABLE B-1: SUMMARY CONDITIONS
OF PROVIDENCE CHANNEL SCENARIOS

PROVIDENCE CHANNEL SCENARIOS

SCENARIO	VISIBILITY	RANDOM ERROR	BIAS ERROR	DEVICE
P0	UNLIMITED /RADAR	10 m (32 ft) 2 drms	20 m (67 ft) 200° T	A
P1	0.25 nm	10 m (32 ft) 2 drms	20 m (67 ft) 200° T	A
P3 *	UNLIMITED	NA	NA	NONE
P6 *	ZERO	10 m (32 ft) 2 drms	20 m (67 ft) 200° T	A
P7 *	ZERO	ZERO	ZERO	A
P8 *	ZERO	10 m (32 ft) 2 drms	33 m (109 ft) 232° T	A
P4	0.25 nm	10 m (32 ft) 2 drms	20 m (67 ft) 200° T	B
P5	0.25 nm	10 m (32 ft) 2 drms	20 m (67 ft) 200° T	C

* Test scenarios presented in random order.

QUESTIONS AFTER PROVIDENCE FAMILIARIZATION PO

1. Does this version of Providence allow you to make a representative transit of Providence? Was your transit representative? If not, what was missing or unrealistic? Was the request to stay on the centerline unrealistic?

2. Was the ship realistic? Have you piloted such a ship? Did it perform as you expected for its characteristics? Was the perspective view realistic for the midship house?

3. Please draw your ship track on the chartlet as you think it looked this run. What factors influenced the track?

4. Was this familiarization scenario enough to familiarize you with the simulator, channel, ship, etc? If not what more is needed?

5. Can you describe your attempts to familiarize yourself with Device A? How did you use it in combination with the visual scene? How did you use it in combination with the radar?

6. Would you like another unlimited visibility transit with the radio aid device before practice in limited visibility? (The following transit will be 0.25 nm visibility and no radar).

PLEASE FEEL FREE TO COMMENT ON THESE MATTERS DURING THE DAY

PROVIDENCE SCENARIOS P1 THROUGH P8

The remaining PROVIDENCE scenarios will be as summarized in Table B-1. For each scenario there is a chartlet* repeating the conditions and a questionnaire.

QUESTIONS AFTER PROVIDENCE SCENARIOS P1 THROUGH P8

1. How well did the information available allow you to control the ship? How difficult and how risky was the transit?

2. Please draw the ship track on the chartlet as you think it looked. Was it as you intended?

3. Please describe briefly the techniques you used during the transit.

4. How did the transit compare to a transit you might have made in Providence in limited visibility with radar?

5. Did you find the device useful? How did you use it? Which features did you find useful or not useful?

6. How comfortable are you with the device? What other type of preparation would be helpful?

Note: The individual chartlets available to the pilots for these scenarios are similar to Chartlet P0 (Figure B-6). They have been omitted here to save space.

Appendix C

Instructions to the Pilot

Day 2: Experiment

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APPENDIX C

RADIO AIDS EXPERIMENT PILOT BRIEFING-
DAY 2 (EXPERIMENT)

INTRODUCTION

Day 2 will begin with a scenario designed to re-familiarize you with the simulator, the response characteristics of the ship, and radio aid Device A. Some random and bias error should be expected from these devices as was encountered on Day 1. Like Day 1, some transits will be made under conditions of reduced visibility so that we can examine the tradeoffs among device characteristics, positioning error, and visibility.

RADIO AIDS

(Researcher reviews the first day's briefing on the three (3) Radio Aid Devices).

SYSTEM ERROR

(Researcher reviews the first day's briefing on Random Error and Bias Error).

SHIP PARTICULARS AND BRIDGE LAYOUT

(Researcher reviews the first day's briefing on the characteristics of ownship.)

The only difference for the SS Barbara, which will be used today (Day 2) is the EOT settings:

EOT	RPM	SPEED (KTS)
DEAD SLOW	11	1.7
SLOW	22	3.4
HALF	44	6.5
FULL	88	12.5

STONE CHANNEL FOR DAY 2

The experimental channel, Stone Channel, is 500 feet wide with a single 35^{o} turn to port. There are no bank effects. The channel's depth will provide sufficient under keel clearance for the ship. The chart for the channel is attached as Figure C-1 (Chartlet E0).

The current direction will be 341^{o} T throughout the scenario. That is, following in the first leg and from broad on the port quarter in Leg 2. The current speed will be 1.3 knots at the start and will continue to decrease throughout the scenario as shown on the chartlet.

The wind will be from 161^{o} T and will be gusting up to 30 knots.

You will be making multiple runs on this channel for the purposes of evaluating device usefulness under a variety of conditions. Table C-1 shows the conditions (visibility, random error, bias error, and device) associated with each run.

STONE CHANNEL FAMILIARIZATION SCENARIO

This scenario is designed to familiarize you with the channel. Visibility will be unlimited. Device A will be available for comparing the situation on the display with the view "out-the-window" and on the radar.

For the familiarization scenario only, ownship will start just outside the channel (356 feet right of the centerline and 1.3 nm below the turn) with a speed through the water of 6.5 knots and a heading of 341^{o} T. See Chartlet E0. Please maneuver to the centerline as quickly as is prudent and stay as close to a strictly defined "centerline" as is practical. As a strict test of the devices' effectiveness, we will ask you to keep the ship on the centerline except when making turns. You will be free to use the EOT to increase RPM in the turn if you so desire. Please announce the change. Negotiate the turn by your own technique and return to the centerline and slower speed as soon as prudent in the next leg.

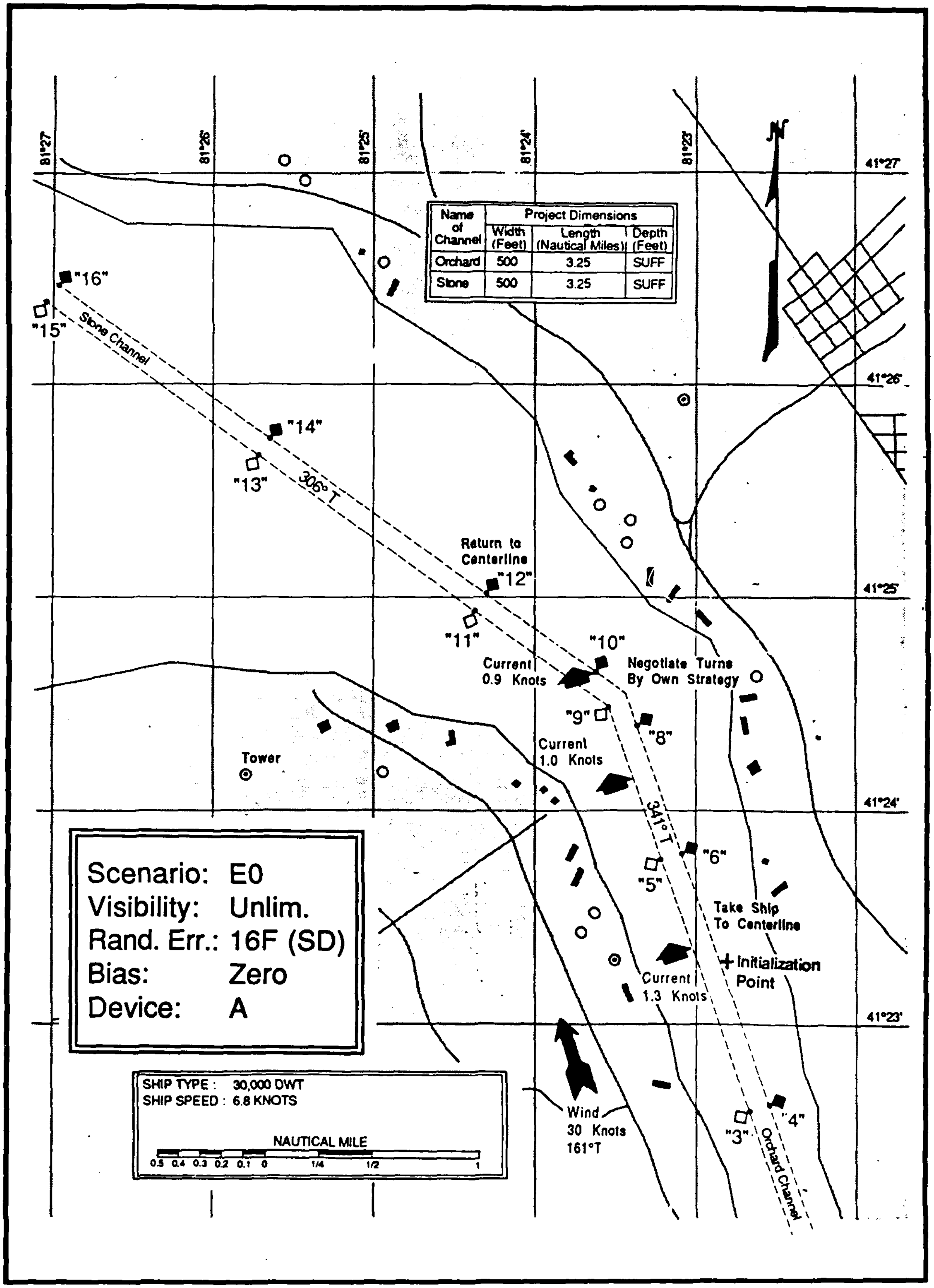
81°27'
81°26'
81°25'
81°24'
81°23'
41°27'
41°26'
41°25'
41°24'
41°23'
N
Name of Channel
Project Dimensions
Width (Feet)
Length (Nautical Miles)
Depth (Feet)
Orchard 500 3.25 SUFF
Stone 500 3.25 SUFF
"16"
"15"
Stone Channel
"14"
"13"
306° T
Return to Centerline
"12"
"11"
"10"
Current 0.9 Knots
Negotiate Turns By Own Strategy
"9"
"8"
Current 1.0 Knots
Tower
341°T
"6"
"5"
Take Ship To Centerline
Initialization Point
Current 1.3 Knots
Scenario: E0
Visibility: Unlim.
Rand. Err.: 16F (SD)
Bias: Zero
Device: A
SHIP TYPE : 30,000 DWT
SHIP SPEED : 6.8 KNOTS
NAUTICAL MILE
0.5 0.4 0.3 0.2 0.1 0 1/4 1/2 1
Wind 30 Knots 161°T
"4"
"3"
Orchard Channel

TABLE C-1: SUMMARY CONDITIONS
OF STONE CHANNEL SCENARIOS

STONE CHANNEL SCENARIOS

SCENARIO	VISIBILITY	RANDOM ERROR	BIAS ERROR	DEVICE
E0	UNLIMITED	10m (32ft) 2 drms	ZERO	A
E1	UNLIMITED	NA	NA	NONE
E2	0.25 nm	10m (32ft) 2 drms	ZERO	A
E3	0.25 nm	18m (60ft) 2 drms	ZERO	A
E4	0.25 nm	10m (32ft) 2 drms	16m (53 ft) 216° T	A
E5	0.25 nm	10m (32ft) 2 drms	16m (53 ft) 216° T	B
E6	0.25 nm	10m (32ft) 2 drms	16m (53 ft) 216° T	C
E7	0.25 nm	10m (32ft) 2 drms	32m (106 ft) 216° T	A
E8	ZERO	10m (32ft) 2 drms	16m (53 ft) 216° T	A

Note: E1 - E8 presented in random order.

START OF DAY 2

AFTER STONE CHANNEL FAMILIARIZATION SCENARIO EO

1. How did this transit compare with a comparable transit at sea? Was the request that you stay on the centerline unrealistic? Was the speed appropriate for the conditions?

2. Was the ship realistic? Have you piloted such a ship? Did it perform as you expected for its characteristics? Was the perspective view realistic for the midship house? Did the wind and current behave realistically?

3. Please draw your ship track on the chartlet as you think it looked during this transit? What factors influenced the track?

4. Was this familiarization scenario enough to familiarize you with the simulator, channel, ship, etc? If not what more is needed?

5. Can you describe your attempts to re-familiarize yourself with Device A? How did you use it in combination with the visual scene? How did you use it in combination with the radar?

6. Would you like another unlimited visibility transit with the radio aid device? The following scenarios may have restricted visibility and will have no radar.

PLEASE FEEL FREE TO COMMENT ON THESE MATTERS DURING THE DAY

STONE CHANNEL SCENARIOS E1 THROUGH E8

The remaining STONE CHANNEL SCENARIOS are as summarized in Table C-1. For each scenario there is a chartlet* repeating the conditions and a questionnaire.

These scenarios will start with ownship 135 feet right of the channel centerline, approximately 1.3 nm below the turn, and with a heading of 341°T as indicated on the chartlets. Ownship's speed through the water will be approximately 6.5 knots. Please stay as close to a strictly defined "centerline" as is practical. You will be free to use the EOT to increase RPM in the turn if you so desire. Please announce the change. Negotiate the turn by your own technique and return to the centerline and slower speed as soon quickly as possible in the next leg.

AFTER STONE CHANNEL SCENARIOS E1 THROUGH E8

1. How well did the information available allow you to control the ship? How difficult and how risky was the transit? Was the speed appropriate?

2. Please draw the ship track on the chartlet as you think it looked. Was it as you intended?

3. Please describe briefly the techniques you used during the transit.

4. How did the transit differ from a transit you might have made at sea.

Note: The individual chartlets available to the pilots for these scenarios are similar to Chartlet E0 (Figure C-1). They have been omitted here to save space.

Appendix D

Ownship Track Plots of Test Subject Performance for Various Experimental Conditions

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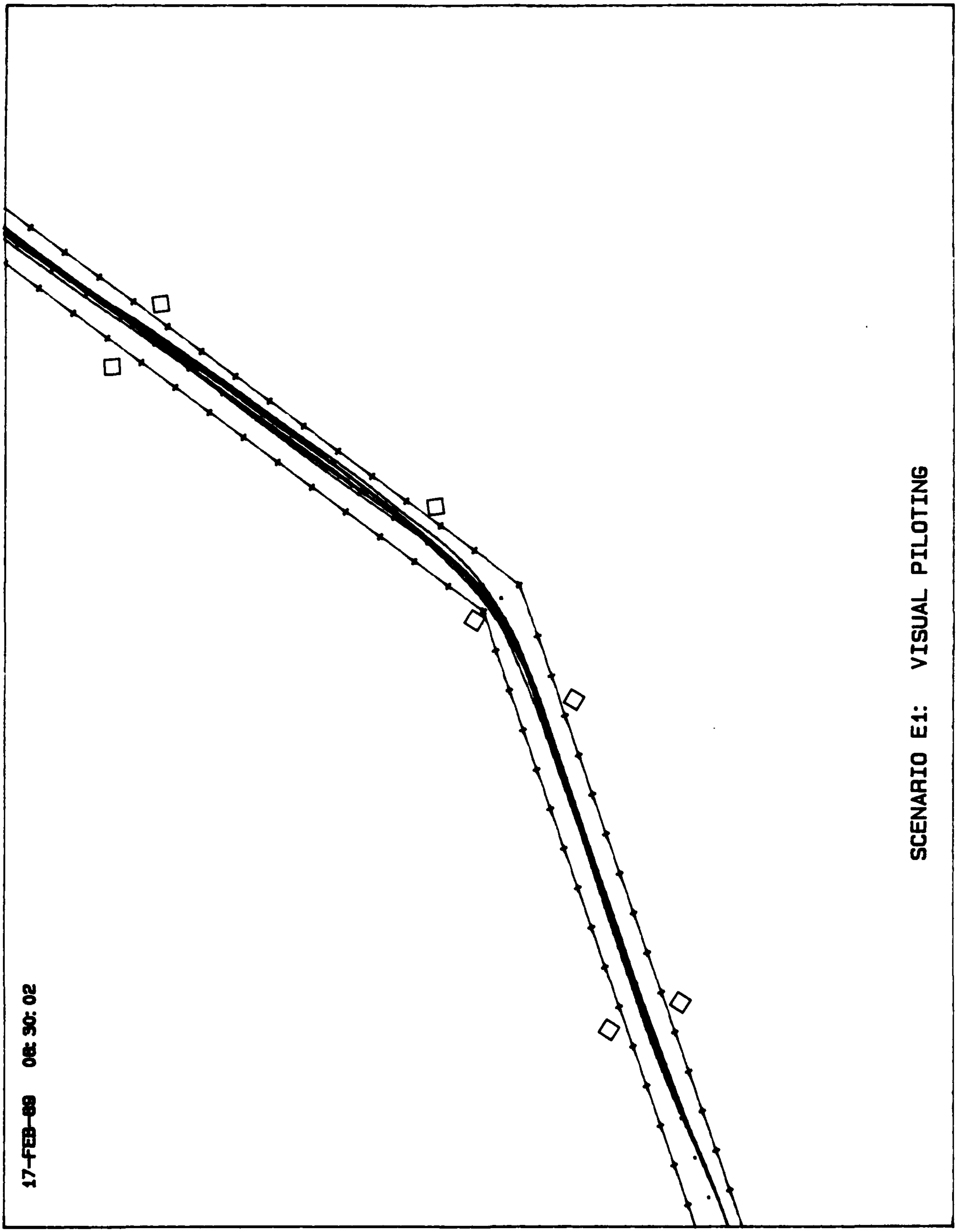
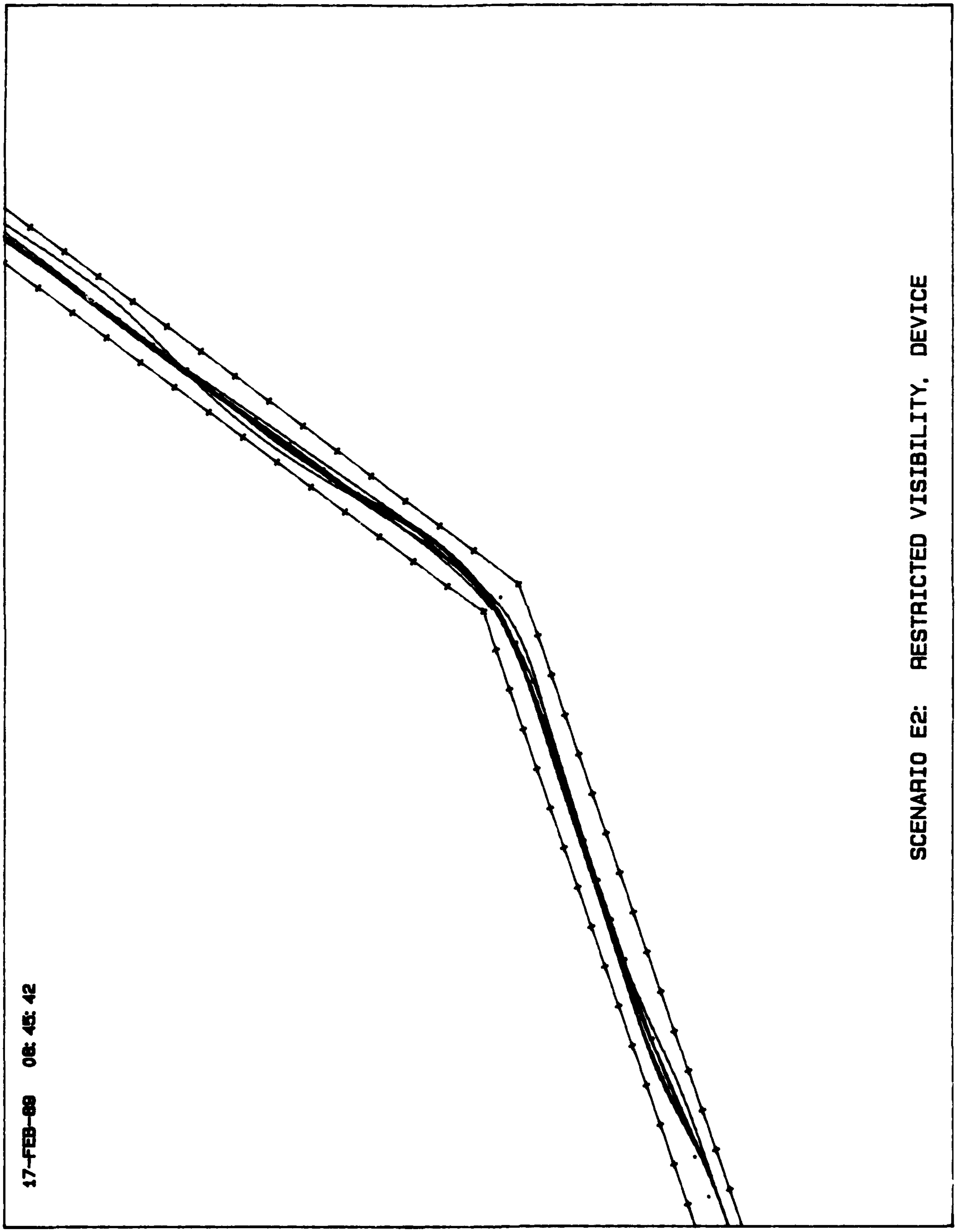
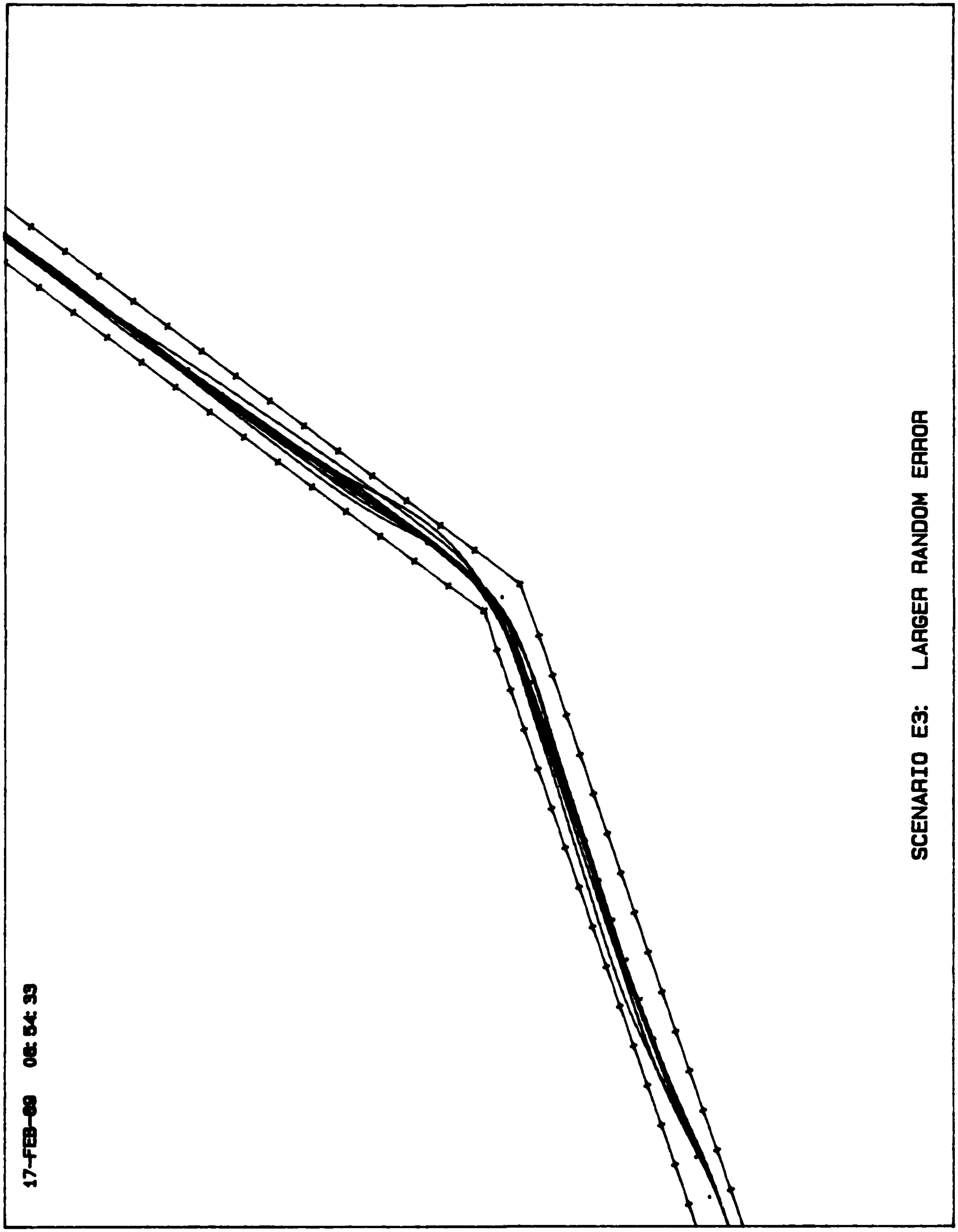
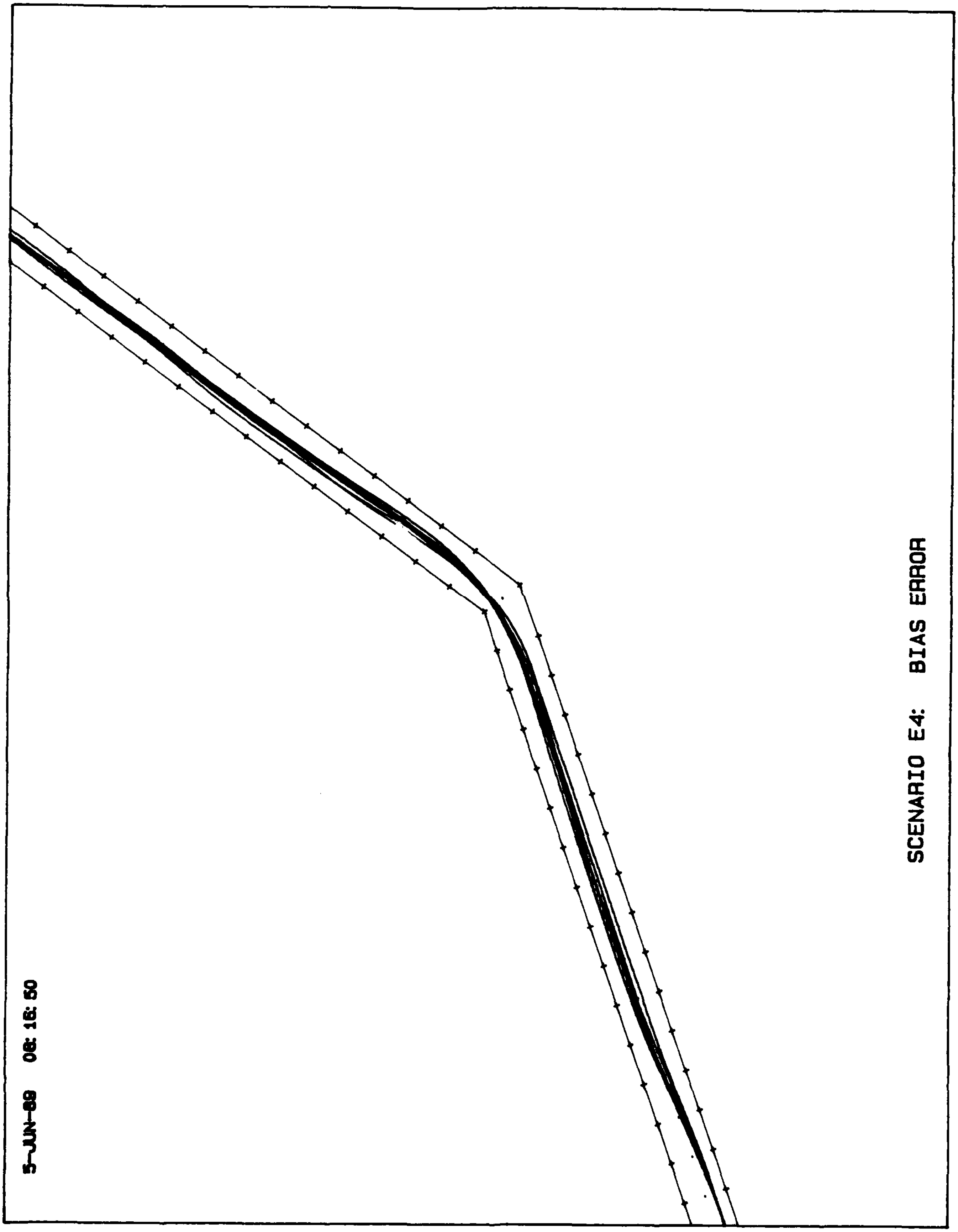
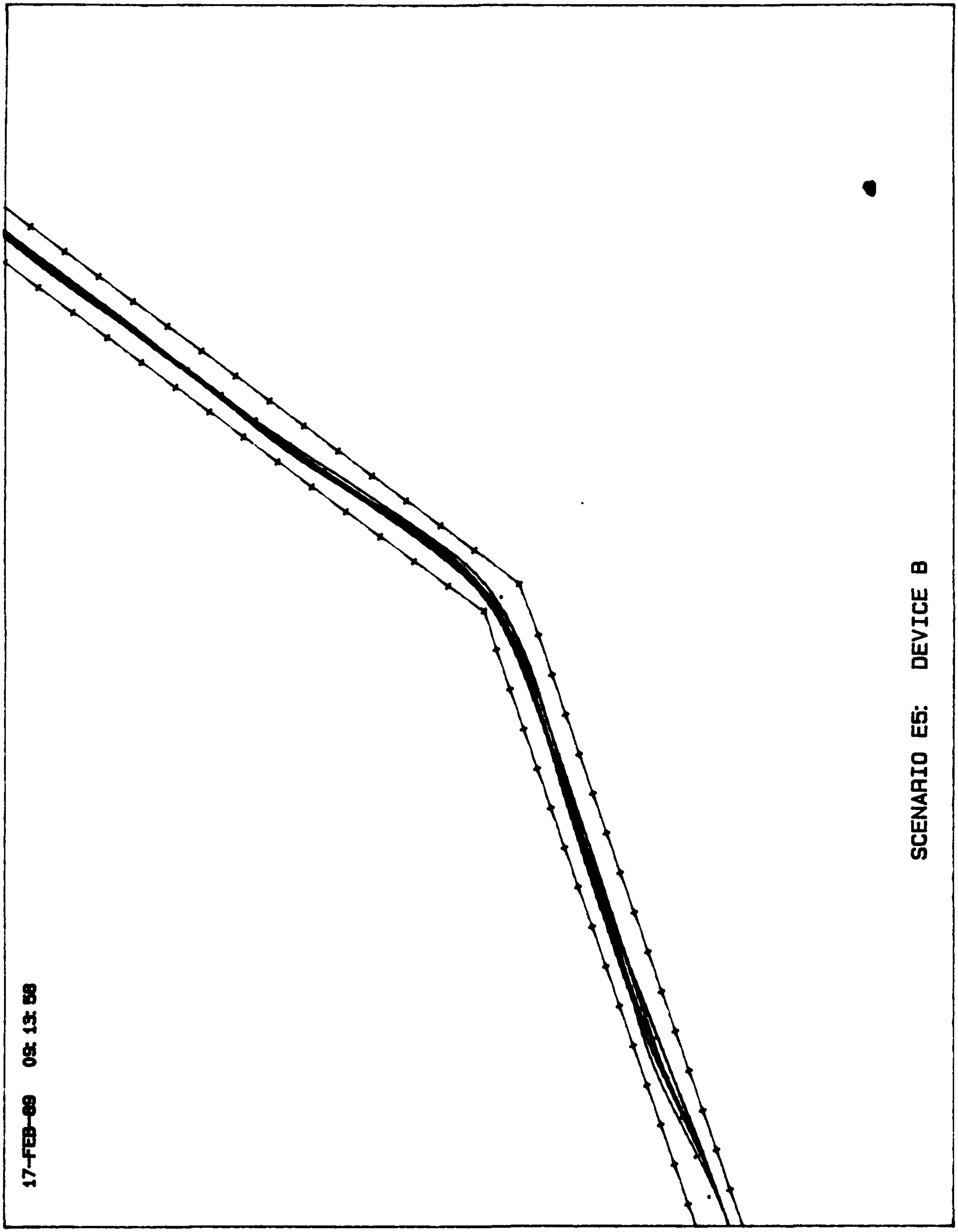

17-FEB-89 08:30:02
SCENARIO E1: VISUAL PILOTING

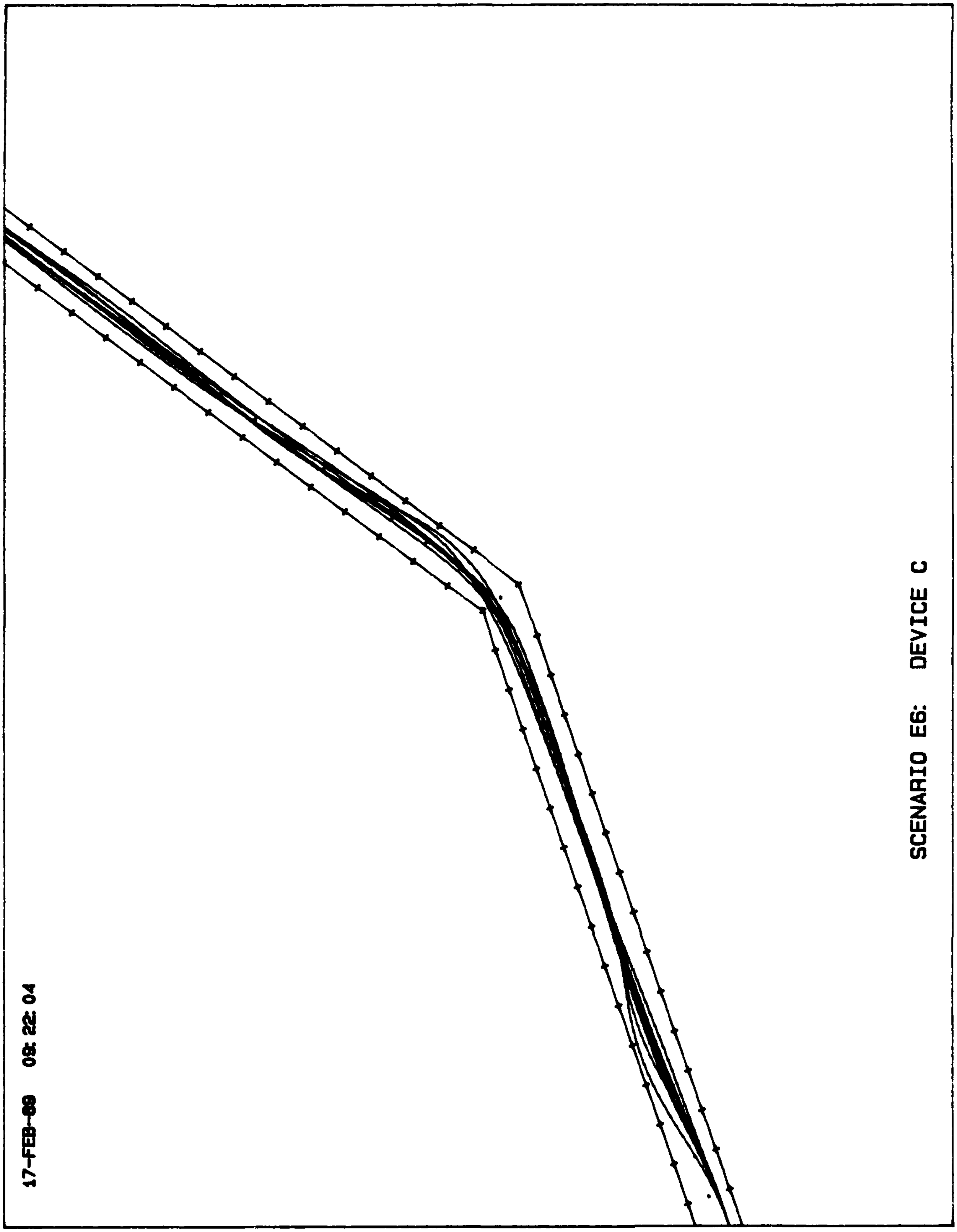

SCENARIO E2: RESTRICTED VISIBILITY, DEVICE
17-FEB-88 06:45:42

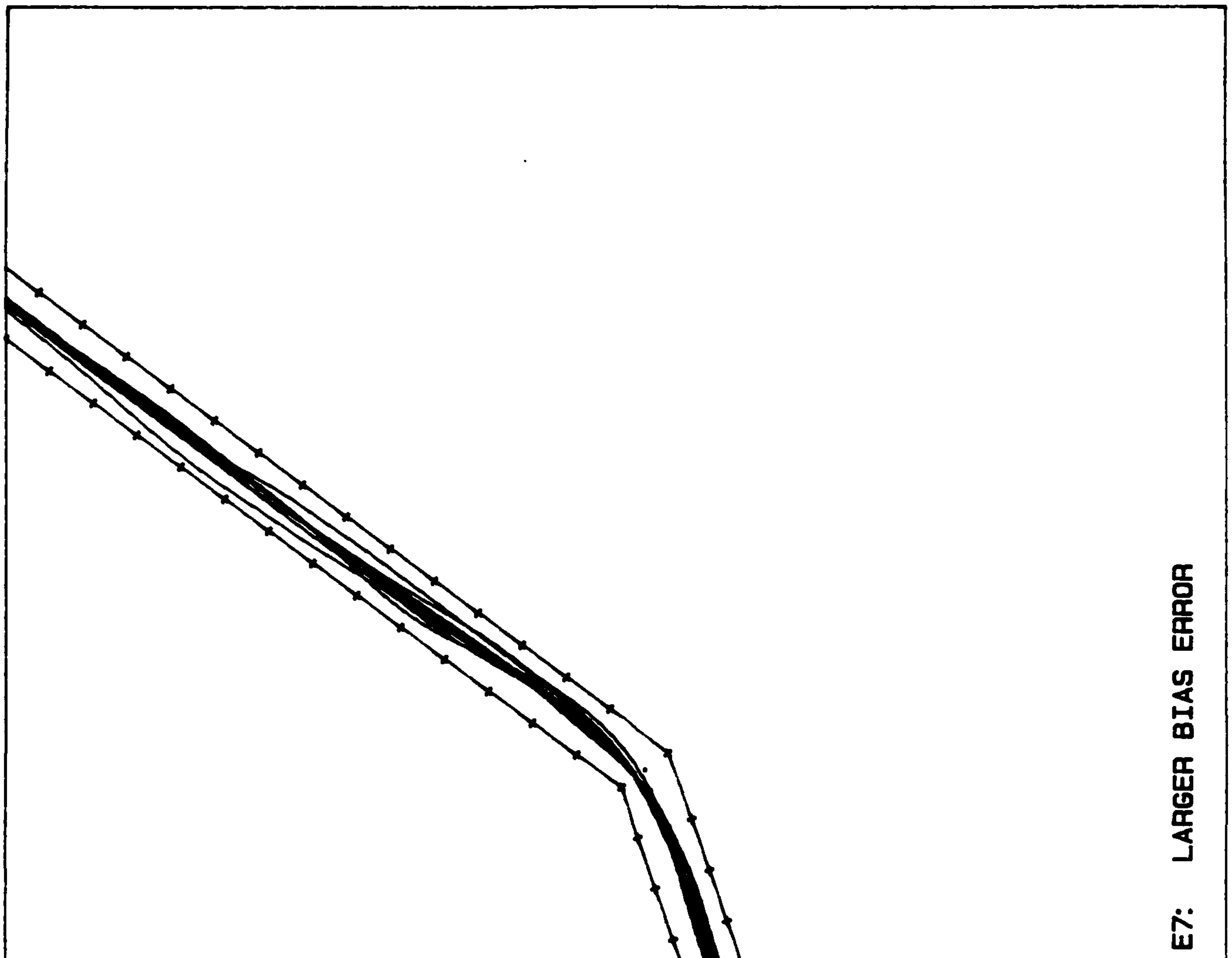

17-FEB-89 08:54:33
SCENARIO E3: LARGER RANDOM ERROR

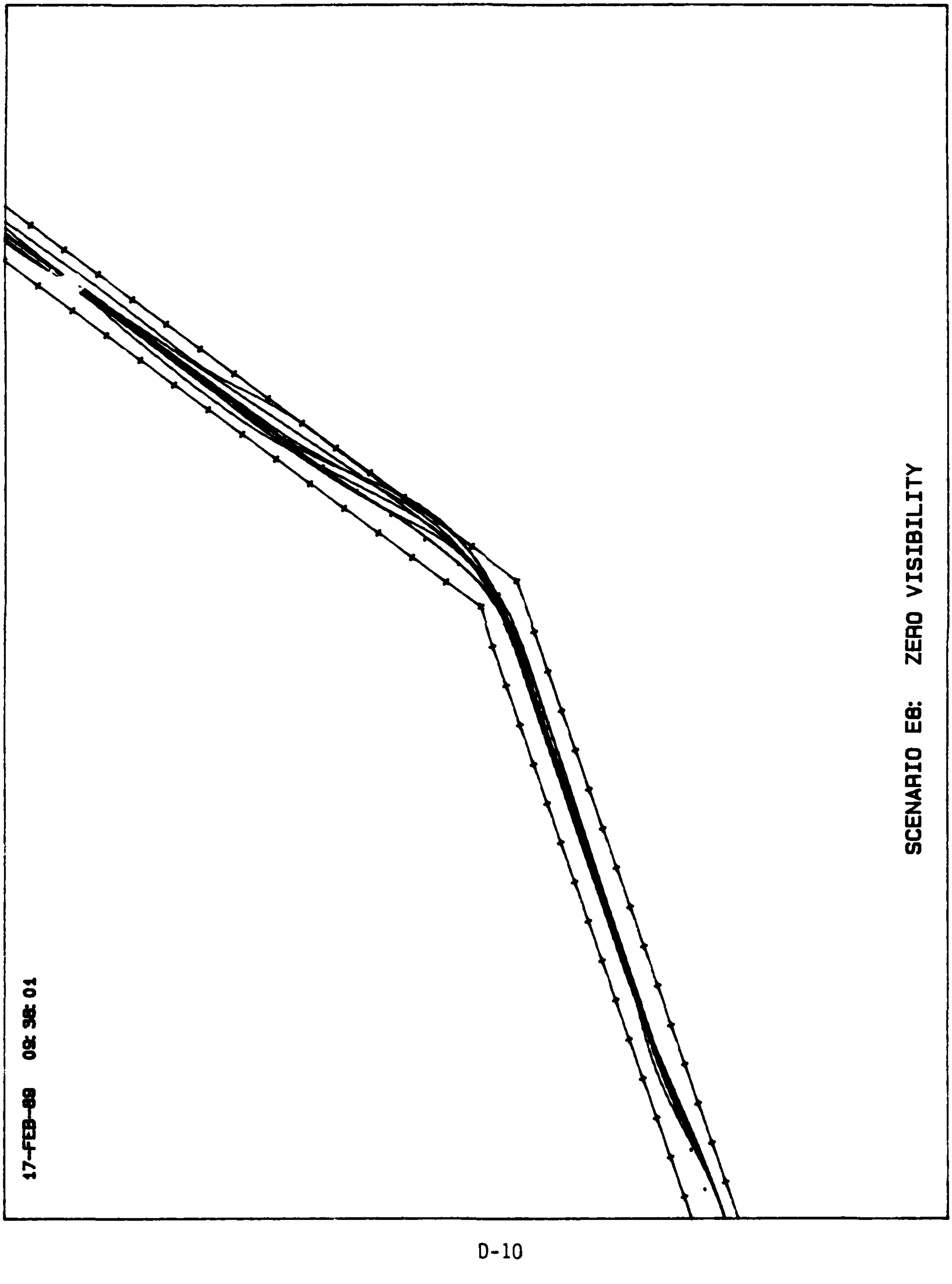


SCENARIO E4: BIAS ERROR


17-FEB-88 09:13:58
SCENARIO E5: DEVICE B


17-FEB-89 09:22:04
SCENARIO E6: DEVICE C


SCENARIO E7: LARGER BIAS ERROR
17-FEB-88 09:30:04


17-FEB-89 09:38:01
SCENARIO E6: ZERO VISIBILITY

Appendix E

Statistical Description of Test Subject Performance for Various Experimental Conditions

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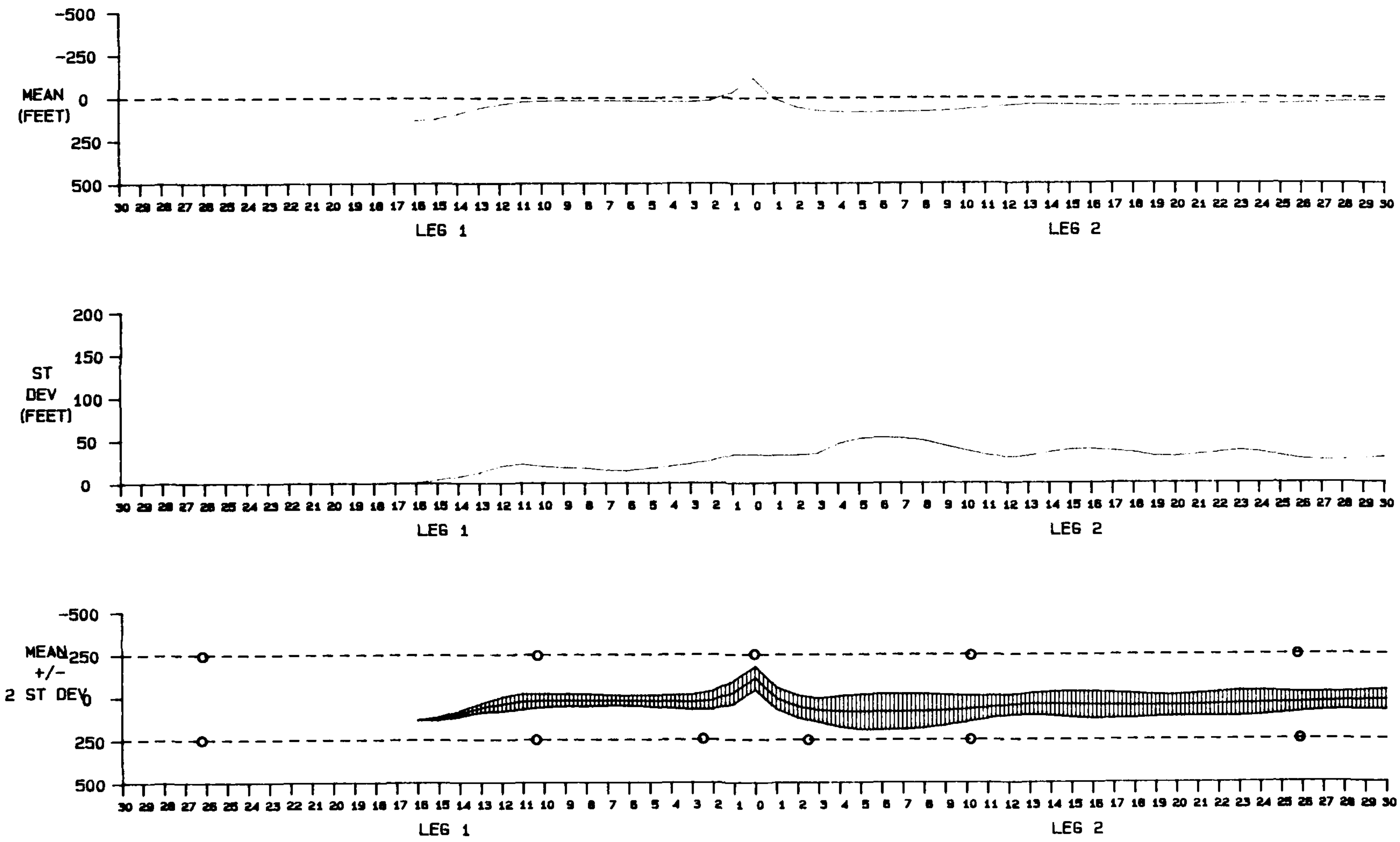
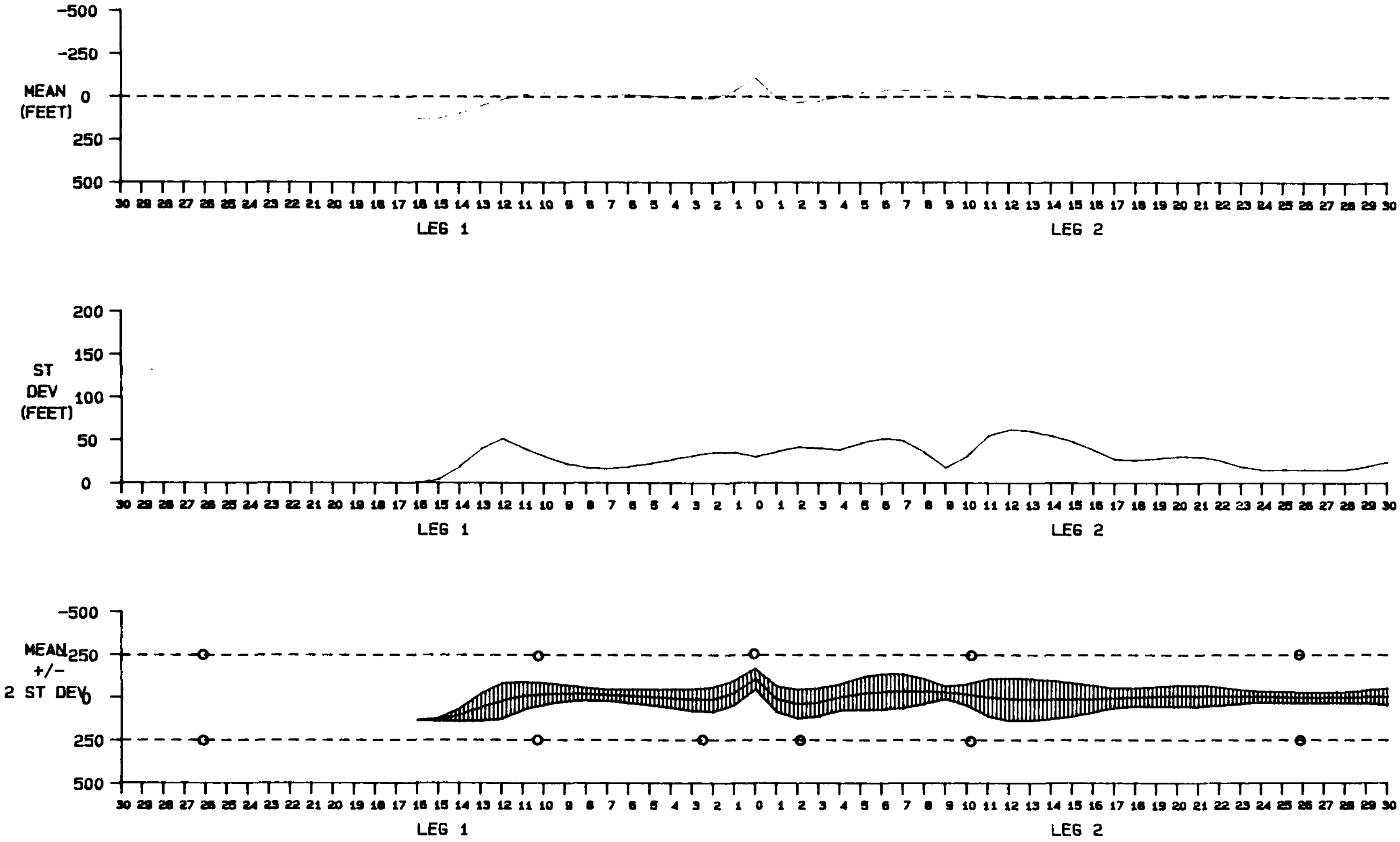
7-FEB-89 15: 05: 58

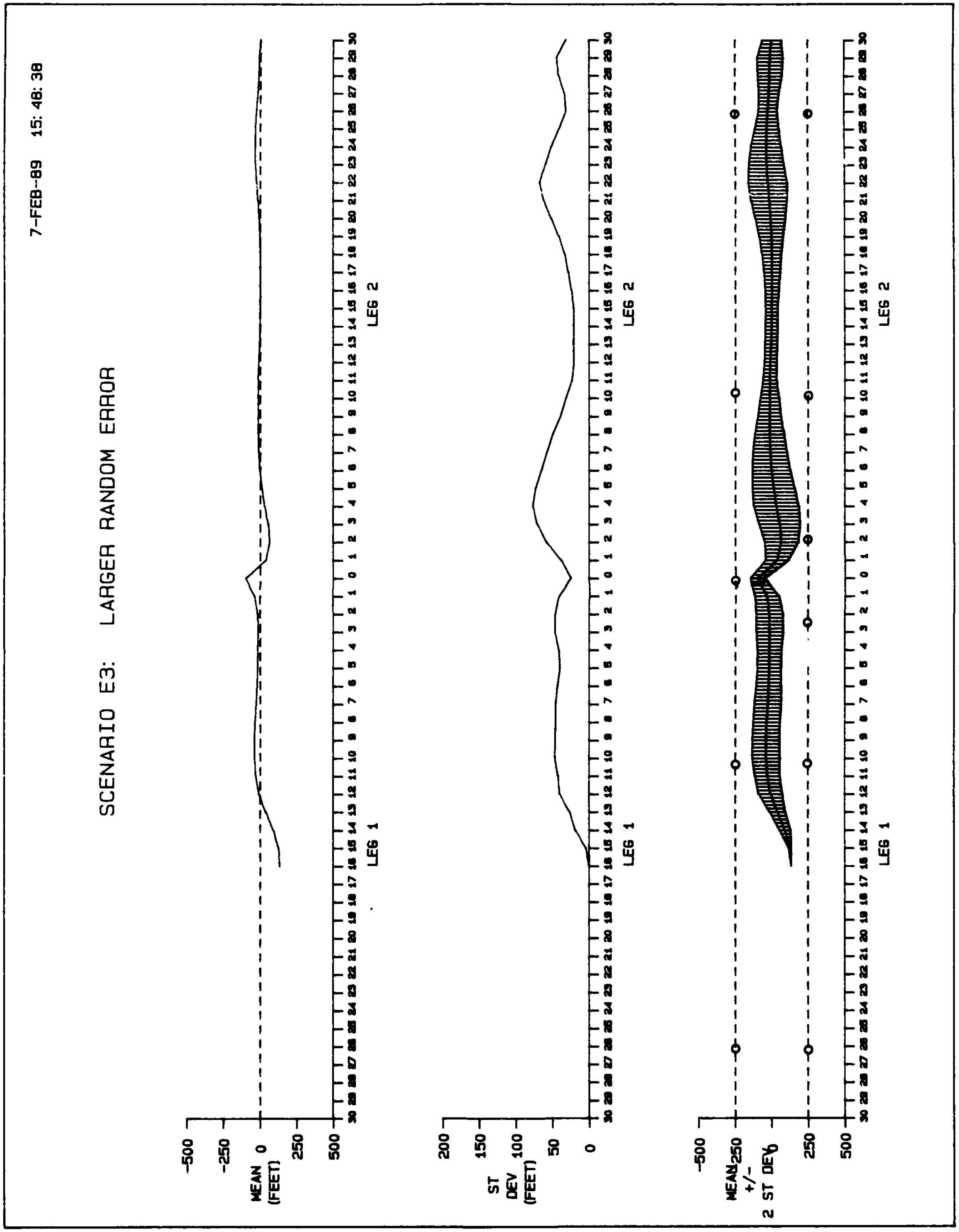
SCENARIO E1 VISUAL PILOTING

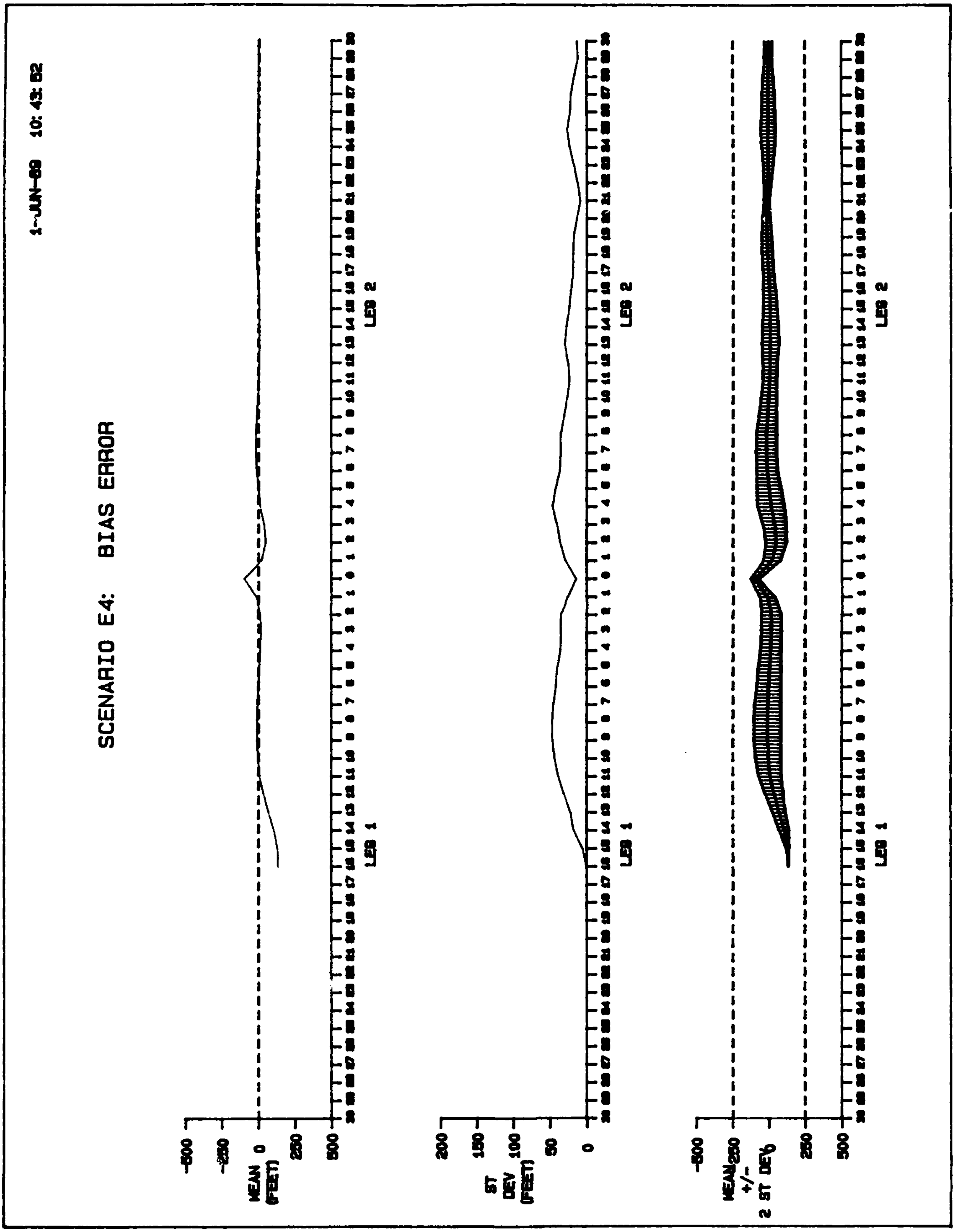


7-FEB-89 15:22:51

SCENARIO E2: RESTRICTED VISIBILITY, DEVICE

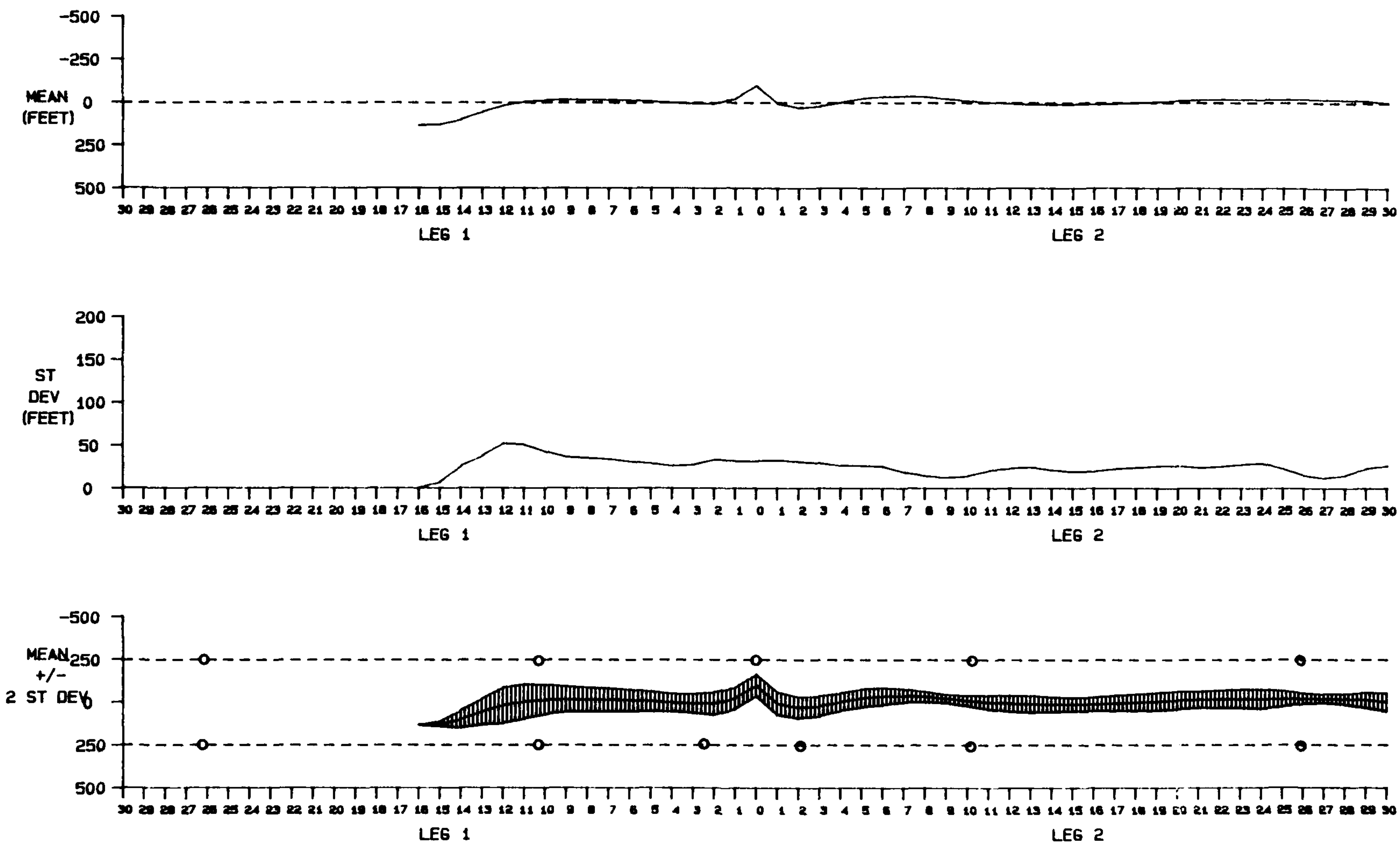


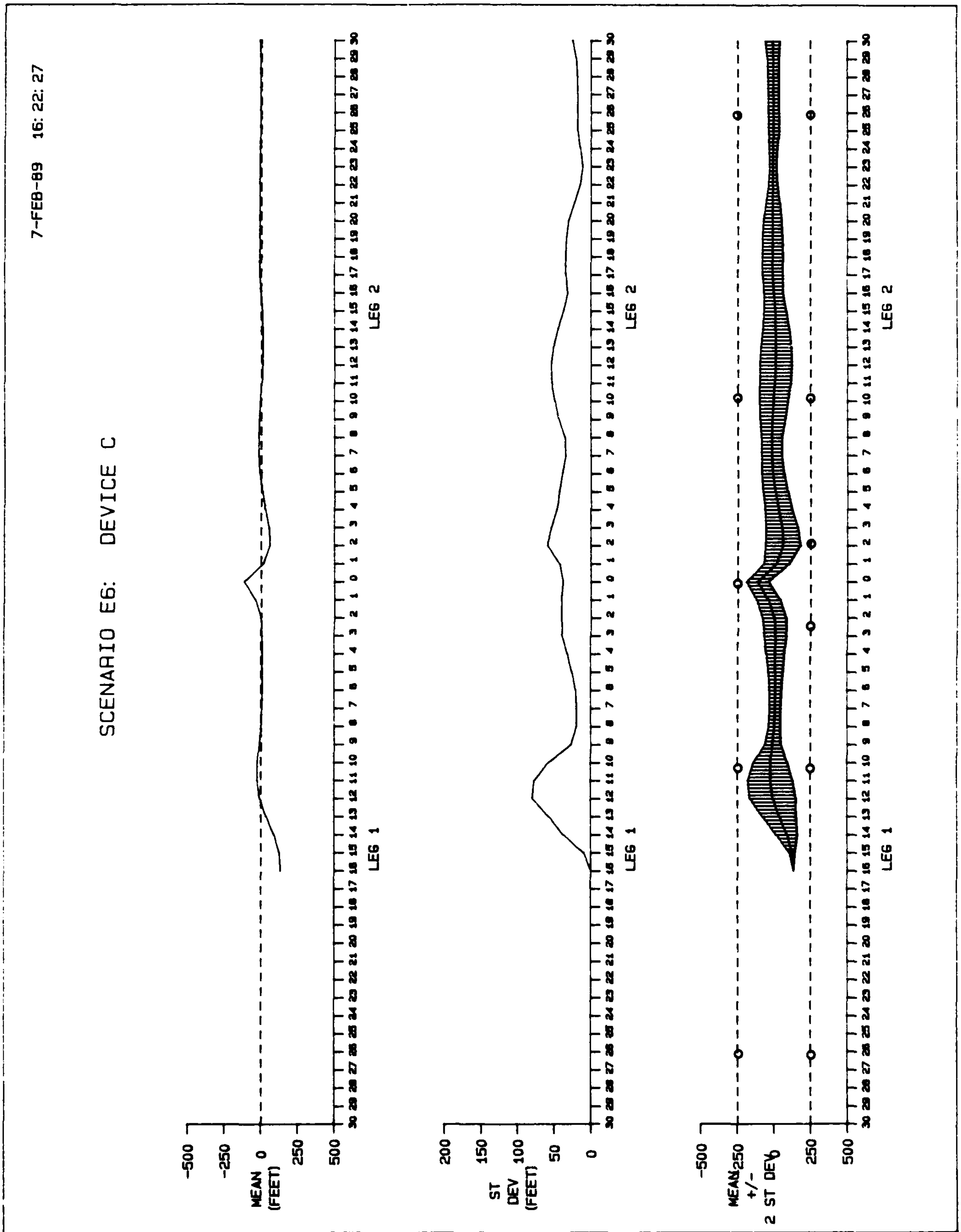

SCENARIO E3: LARGER RANDOM ERROR
7-FEB-89 15:48:38
MEAN (FEET)
-500
-250
0
250
500
ST DEV (FEET)
200
150
100
50
0
MEAN +/- 2 ST DEV
LEG 1
LEG 2

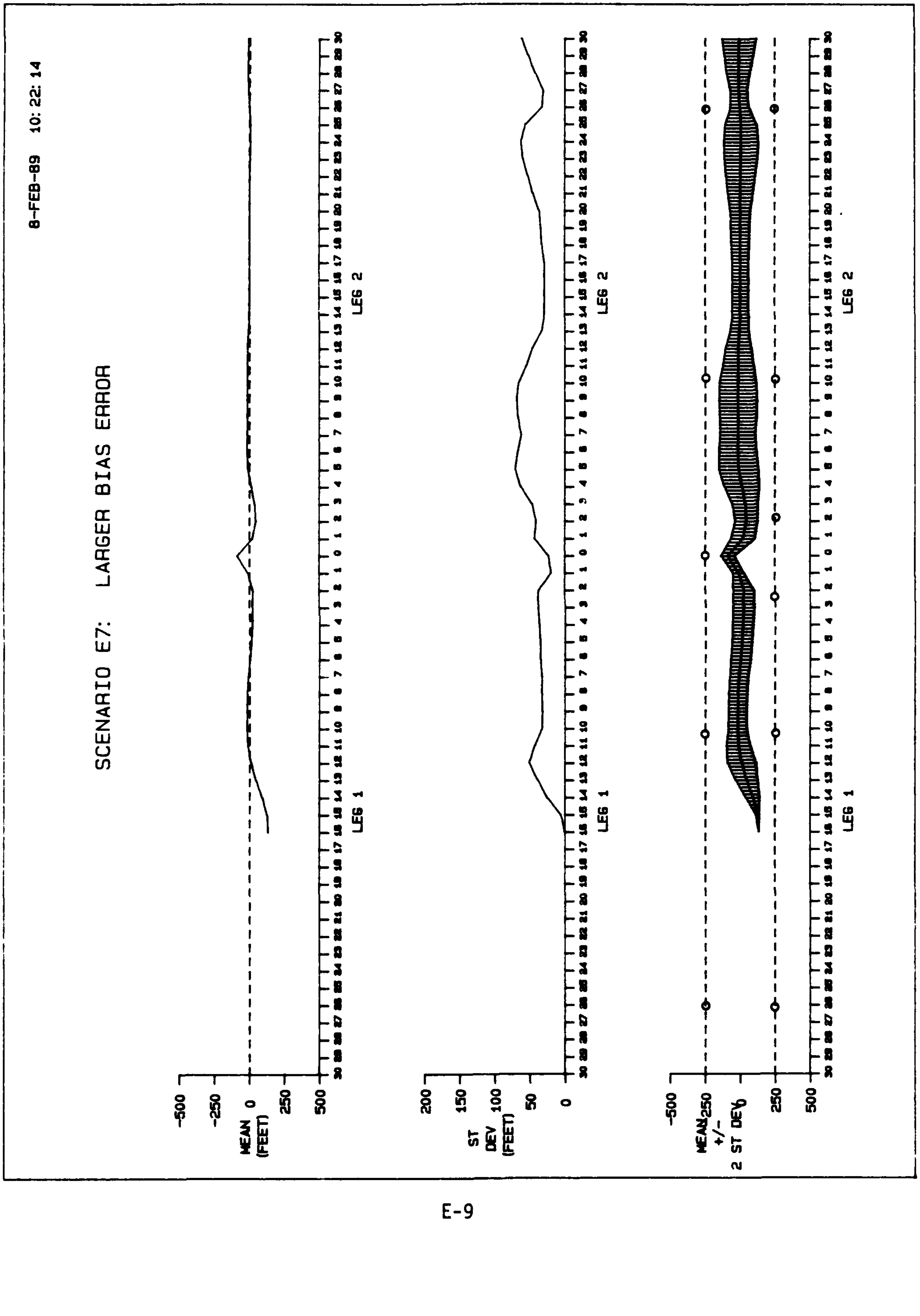

SCENARIO E4: BIAS ERROR
1-JUN-89 10:43:52
MEAN (FEET)
ST DEV (FEET)
MEAN +/- 2 ST DEV
LEG 1
LEG 2

7-FEB-89 16: 12: 31

SCENARIO E5: DEVICE B

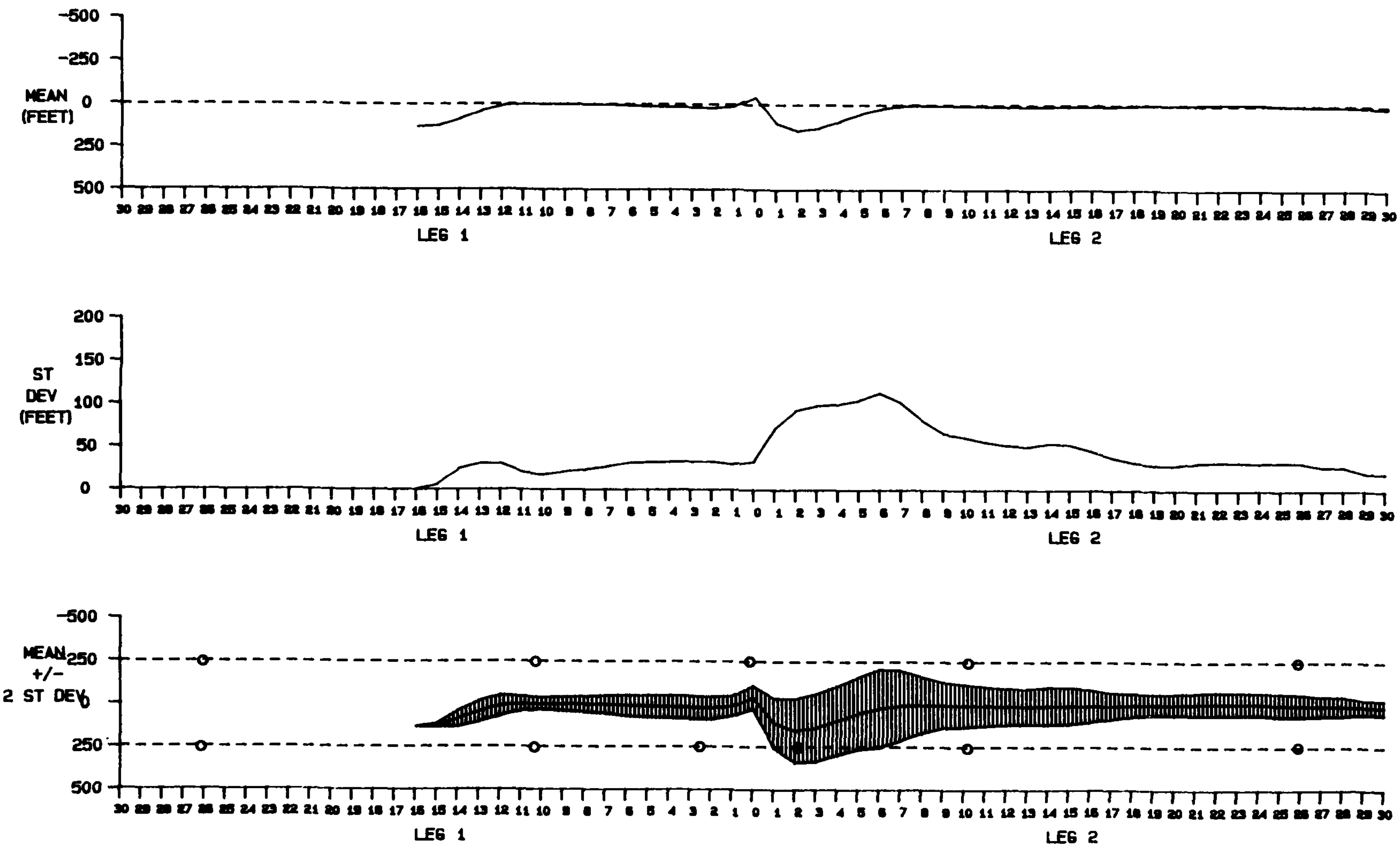



SCENARIO E6: DEVICE C
7-FEB-89 16:22:27
MEAN (FEET)
-500
-250
0
250
500
ST DEV (FEET)
200
150
100
50
0
MEAN +/- 2 ST DEV
LEG 1
LEG 2


8-FEB-89 10: 22: 14
SCENARIO E7: LARGER BIAS ERROR
MEAN (FEET)
-500
-250
0
250
500
ST DEV (FEET)
200
150
100
50
0
MEAN +/- 2 ST DEV
LEG 1
LEG 2

8-FEB-89 10: 31: 59

SCENARIO E8: ZERO VISIBILITY



Appendix F

Statistical Comparisons of Test Subject Performance for Various Experimental Conditions

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TABLE F-1: Comparison of RA Piloting Performance with Two Levels of Random Error

	10 m (2 drms) (Scenario E2)				18 m (2 drms) (Scenario E3)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	19.4	52.3	7	0.002	-9.9	40.9	8	0.000	F=1.64 N.S.	t=1.19 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	-18.8	17.6	7	0.000	-33.3	45.7	8	0.000	F=6.74 $p \leq 0.05$		⬅
TURN PULLOUT	39.8	42.3	7	0.000	54.1	71.3	8	0.036	F=1.17 N.S.	t=3.22 $p \leq 0.01$	⬅
RECOVERY WITH CROSSCURRENT	-35.8	52.4	7	0.001	-11.1	57.7	8	0.001	F=1.21 N.S.	t=0.87 N.S.	□
TRACKKEEPING WITH CROSSCURRENT	9.1	38.1	7	0.000	-26.1	68.6	8	0.007	F=3.24 $p \leq 0.10$		⇦

<u>KEY:</u>

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-2: Comparison of RA Performance with Lower Random Error versus Visual Piloting

	10 m (2 drms) (Scenario E2)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	19.4	52.3	7	0.002	39.0	20.4	8	0.000	$F=6.57$ $p\leq 0.05$		➡
TRACKKEEPING WITHOUT CROSSCURRENT	-18.8	17.6	7	0.000	19.7	14.4	8	0.000	$F=1.49$ N.S.	$t=4.59$ $p\leq 0.01$	☐
TURN PULLOUT	39.8	42.3	7	0.000	78.8	34.6	8	0.001	$F=1.49$ N.S.	$t=1.94$ $p\leq 0.10$	⇦
RECOVERY WITH CROSSCURRENT	-35.8	52.4	7	0.001	86.1	53.5	8	0.021	$F=1.04$ N.S.	$t=4.45$ $p\leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	9.1	38.1	7	0.000	53.2	34.6	8	0.000	$F=1.21$ N.S.	$t=2.33$ $p\leq 0.05$	⬅

KEY:

☐ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-3: Comparison of RA Performance with Higher Random Error versus Visual Piloting

REGION	18 m (2 drms) (Scenario E3) MN (ft)	SD (ft)	N	RRF	Visual Piloting (Scenario E1) MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	-9.9	40.9	8	0.000	39.0	20.4	8	0.000	$F=4.02$ $p \le 0.05$		→
TRACKKEEPING WITHOUT CROSSCURRENT	-33.3	45.7	8	0.000	19.7	14.4	8	0.000	$F=10.07$ $p \le 0.01$		→
TURN PULLOUT	54.1	71.3	8	0.036	78.8	34.6	8	0.001	$F=4.25$ $p \le 0.05$		→
RECOVERY WITH CROSSCURRENT	-11.1	57.7	8	0.001	86.1	53.5	8	0.021	$F=1.16$ N.S.	$t=3.49$ $p \le 0.01$	←
TRACKKEEPING WITH CROSSCURRENT	-26.1	68.6	8	0.007	53.2	34.6	8	0.000	$F=3.93$ $p \le 0.05$		→

KEY:

☐ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \le 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \le 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-4: Comparison of RA Piloting Performance with 16 m and 0 m Bias Errors

REGION	16 m (53 ft) 216° T (Scenario E4)				0 m (0 ft) 000° (Scenario E2)				F	t	RESULT
	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF			
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	19.4	52.3	7	0.002	F=2.96 N.S.	t=0.48 N.S.	☐
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	-18.8	17.6	7	0.000	F=7.34 $p \leq 0.05$		➡
TURN PULLOUT	37.0	40.8	7	0.000	39.8	42.3	7	0.000	F=1.07 N.S.	t=0.13 N.S.	☐
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	-35.8	52.4	7	0.001	F=2.02 N.S.	t=0.75 N.S.	☐
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	9.1	38.1	7	0.000	F=4.68 $p \leq 0.10$		⇦

KEY:

☐ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-5: Comparison of RA Piloting Performance with 32 m and 16 m Bias Error

	32 m (106 ft) 216° T (Scenario E7)				16 m (53 ft) 216° (Scenario E4)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	9.9	51.8	8	0.000	30.4	32.9	7	0.000	F=2.84 N.S.	t=0.93 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	5.7	35.4	8	0.000	-12.8	47.7	7	0.000	F=1.82 N.S.	t=0.84 N.S.	□
TURN PULLOUT	12.4	63.6	8	0.005	37.0	40.8	7	0.000	F=2.43 N.S.	t=0.90 N.S.	□
RECOVERY WITH CROSSCURRENT	-17.2	67.3	8	0.005	-16.9	36.8	7	0.000	F=3.34 $p \leq 0.10$		⇨
TRACKKEEPING WITH CROSSCURRENT	10.3	63.2	8	0.002	-20.6	17.6	7	0.000	F=12.9 $p \leq 0.01$		➡

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

Radio Aids 0010

TABLE F-6: Comparison of RA Piloting Performance with 32 m and 0 m Bias Error

	32 m (106ft) 216° T (Scenario E7)				0 m (0ft) 000° (Scenario E2)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	9.9	51.8	8	0.000	19.4	52.3	7	0.002	F=1.04 N.S.	t=0.354 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	5.7	35.4	8	0.000	-18.8	17.6	7	0.000	F=4.05 $p \leq 0.10$		⇨
TURN PULLOUT	12.4	63.6	8	0.005	39.8	42.3	7	0.000	F=2.26 N.S.	t=0.990 N.S.	□
RECOVERY WITH CROSSCURRENT	-17.2	67.3	8	0.005	-35.8	52.4	7	0.001	F=1.65 N.S.	t=0.600 N.S.	□
TRACKKEEPING WITH CROSSCURRENT	10.3	63.2	8	0.002	9.1	38.1	7	0.000	F=2.75 N.S.	t=0.94 N.S.	□

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

Radio Aids 0011

TABLE F-7: Comparison of RA Piloting Performance with Zero Bias Error versus Visual Piloting

	0 m (0 ft) 000° T (Scenario E2)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	19.4	52.3	7	0.002	39.0	20.4	8	0.000	F=6.57 $p \leq 0.05$		➡
TRACKKEEPING WITHOUT CROSSCURRENT	-18.8	17.6	7	0.000	19.7	14.4	8	0.000	F=1.49 N.S.	t=4.59 $p \leq 0.01$	□
TURN PULLOUT	39.8	42.3	7	0.000	78.8	34.6	8	0.001	F=1.49 N.S.	t=1.94 $p \leq 0.10$	⇦
RECOVERY WITH CROSSCURRENT	-35.8	52.4	7	0.001	86.1	53.5	8	0.021	F=1.04 N.S.	t=4.45 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	9.1	38.1	7	0.000	53.2	34.6	8	0.000	F=1.21 N.S.	t=2.33 $p \leq 0.05$	⬅

KEY:

- □ NO STATISTICAL DIFFERENCES
- ⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level
- ➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-8: Comparison of RA Performance with Lower Bias Error versus Visual Piloting

	16 m (53 ft) 216°T (Scenario E4)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	39.0	20.4	8	0.000	F=2.60 N.S.	t=0.598 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	19.7	14.4	8	0.000	F=10.9 $p \leq 0.01$		➡
TURN PULLOUT	37.0	40.8	7	0.000	78.8	34.6	8	0.001	F=1.38 N.S.	t=2.13 $p \leq 0.10$	⇦
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	86.1	53.5	8	0.021	F=2.11 N.S.	t=4.40 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	53.2	34.6	8	0.000	F=3.86 $p \leq 0.10$		⇦

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

Radio Aids 0013

TABLE F-9: Comparison of RA Performance with Higher Bias Error versus Visual Piloting

REGION	32 m (106 ft) 216 °T (Scenario E7)				Visual Piloting (Scenario E1)						
	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	9.9	51.8	8	0.000	39.0	20.4	8	0.000	F=6.45 $p \leq 0.05$		➡
TRACKKEEPING WITHOUT CROSSCURRENT	5.7	35.4	8	0.000	19.7	14.4	8	0.000	F=6.05 $p \leq 0.05$		➡
TURN PULLOUT	12.4	63.6	8	0.005	78.8	34.6	8	0.001	F=3.37 $p \leq 0.10$		⇨
RECOVERY WITH CROSSCURRENT	-17.2	67.3	8	0.005	86.1	53.5	8	0.021	F=1.58 N.S.	t=3.40 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	10.3	63.2	8	0.002	53.2	34.6	8	0.000	F=3.34 $p \leq 0.10$		⇨

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-10: Comparison of RA Performance with Device A versus Device B

REGION	RA Device A (Scenario E4)				RA Device B (Scenario E5)				F	t	RESULT
	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF			
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	16.9	52.5	8	0.000	F=2.55 N.S.	t=0.60 N.S.	☐
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	-18.5	36.0	8	0.000	F=1.76 N.S.	t=0.26 N.S.	☐
TURN PULLOUT	37.0	40.8	7	0.000	33.3	30.7	8	0.000	F=1.77 N.S.	t=0.09 N.S.	☐
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	-37.9	25.1	8	0.000	F=2.15 N.S.	t=1.27 N.S.	☐
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	-12.5	26.5	8	0.000	F=2.27 N.S.	t= 0.71 N.S.	☐

KEY:

☐ NO STATISTICAL DIFFERENCES	⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level	➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level	DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-11: Comparison of RA Performance with Device B versus Device C

REGION	RA Device B (Scenario E5) MN (ft)	SD (ft)	N	RRF	RA Device C (Scenario E6) MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	16.9	52.5	8	0.000	-9.5	80.0	8	0.010	F=2.32 N.S.	t=0.78 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	-18.5	36.0	8	0.000	12.0	20.8	8	0.000	F=2.99 $p \leq 0.10$		⇨
TURN PULLOUT	33.3	30.7	8	0.000	62.8	59.9	8	0.023	F=3.81 $p \leq 0.05$		⬅
RECOVERY WITH CROSSCURRENT	-37.9	25.1	8	0.000	-17.7	36.0	8	0.000	F=2.06 N.S.	t=1.30 N.S.	□
	-12.5	26.5	8	0.000	-13.5	33.5	8	0.000	F=1.59 N.S.	t= 0.066 N.S.	□

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-12: Comparison of RA Performance with Device A versus Device C

REGION	RA Device A (Scenario E4)				RA Device C (Scenario E6)						
	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	-9.5	80.0	8	0.010	F=5.91 $p \leq 0.05$		⬅
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	12.0	20.8	8	0.000	F=5.25 $p \leq 0.05$		➡
TURN PULLOUT	37.0	40.8	7	0.000	62.8	59.9	8	0.023	F=2.16 N.S.	t=0.98 N.S.	□
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	-17.7	36.0	8	0.000	F=1.05 N.S.	t=0.04 N.S.	□
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	-13.5	33.5	8	0.000	F=3.62 $p \leq 0.10$	.	⇦

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-13: Comparison of RA Performance with Device A versus Visual Piloting Performance

	RA Device A (Scenario E4)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	39.0	20.4	8	0.000	F=2.6 N.S.	t=0.598 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	19.7	14.4	8	0.000	F=10.9 $p \leq 0.01$		➡
TURN PULLOUT	37.0	40.8	7	0.000	78.8	34.6	8	0.001	F=1.38 N.S.	t=2.13 $p \leq 0.10$	⇦
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	86.1	53.5	8	0.021	F=2.11 N.S.	t=0.04 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	53.2	34.6	8	0.000	F=3.86 $p \leq 0.10$		⇦

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

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TABLE F-14: Comparison of RA Performance with Device B versus Visual Piloting Performance

	RA Device B (Scenario E5)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	16.9	52.5	8	0.000	39.0	20.4	8	0.000	F=6.63 $p \leq 0.05$		→
TRACKKEEPING WITHOUT CROSSCURRENT	-18.5	36.0	8	0.000	19.7	14.4	8	0.000	F=6.24 $p \leq 0.05$		→
TURN PULLOUT	33.3	30.7	8	0.000	78.8	34.6	8	0.001	F=1.27 N.S.	t=2.78 $p \leq 0.05$	←
RECOVERY WITH CROSSCURRENT	-37.9	25.1	8	0.000	86.1	53.5	8	0.021	F=4.54 $p \leq 0.05$		←
TRACKKEEPING WITH CROSSCURRENT	-12.5	26.5	8	0.000	53.2	34.6	8	0.000	F=1.71 N.S.	t= 4.26 $p \leq 0.01$	←

KEY:

☐ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-15: Comparison of RA Performance with Device C versus Visual Piloting Performance

REGION	RA Device C (Scenario E6) MN (ft)	SD (ft)	N	RRF	Visual Piloting (Scenario E1) MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	-9.5	80.0	8	0.010	39.0	20.4	8	0.000	F=15.38 $p \leq 0.01$		➡
TRACKKEEPING WITHOUT CROSSCURRENT	12.0	20.8	8	0.000	19.7	14.4	8	0.000	F=2.09 N.S.	t=0.86 N.S.	□
TURN PULLOUT	62.8	59.9	8	0.023	78.8	34.6	8	0.001	F=2.99 $p \leq 0.10$		⇨
RECOVERY WITH CROSSCURRENT	-17.7	36.0	8	0.000	86.1	53.5	8	0.021	F=2.21 N.S.	t=4.55 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	-13.5	33.5	8	0.000	53.2	34.6	8	0.000	F=1.07 N.S.	t=3.92 $p \leq 0.01$	⬅

KEY:

- □ NO STATISTICAL DIFFERENCES
- ⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level
- ➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

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TABLE F-16: Comparison of RA Piloting Performance under Two Levels of Visibility

	0.25 NM (Scenario E4)				0.0 NM (Scenario E8)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	10.3	30.5	8	0.000	F=1.16 N.S.	t=1.22 N.S.	☐
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	11.4	31.6	8	0.000	F=2.27 N.S.	t=1.14 N.S.	☐
TURN PULLOUT	37.0	40.8	7	0.000	135.6	99.2	8	0.316	F=5.91 $p \leq 0.05$		⬅
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	22.4	114.4	8	0.094	F=9.66 $p \leq 0.01$		⬅
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	7.5	46.1	8	0.000	F=6.85 $p \leq 0.05$		⬅

KEY:

☐ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

TABLE F-17: Comparison of RA Piloting Performance with 0.25 NM Visibility versus Visual Piloting

	0.25 NM (Scenario E4)				Visual Piloting (Scenario E1)						
REGION	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	30.4	32.9	7	0.000	39.0	20.4	8	0.000	F=2.60 N.S.	t=0.598 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	-12.8	47.7	7	0.000	19.7	14.4	8	0.000	F=10.9 $p \leq 0.01$		➡
TURN PULLOUT	37.0	40.8	7	0.000	78.8	34.6	8	0.001	F1.38 N.S.	t=2.13 $p \leq 0.10$	⇨
RECOVERY WITH CROSSCURRENT	-16.9	36.8	7	0.000	86.1	53.5	8	0.021	F=2.11 N.S.	t=4.40 $p \leq 0.01$	⬅
TRACKKEEPING WITH CROSSCURRENT	-20.6	17.6	7	0.000	53.2	34.6	8	0.000	F=3.86 $p \leq 0.10$		⇦

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

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TABLE F-18: Comparison of RA Piloting Performance with zero Visibility versus Visual Piloting

REGION	0.0 NM (Scenario E8)				Visual Piloting (Scenario E1)						
	MN (ft)	SD (ft)	N	RRF	MN (ft)	SD (ft)	N	RRF	F	t	RESULT
RECOVERY WITHOUT CROSSCURRENT	10.3	30.5	8	0.000	39.0	20.4	8	0.000	F=2.22 N.S.	t=0.78 N.S.	□
TRACKKEEPING WITHOUT CROSSCURRENT	11.4	31.6	8	0.000	19.7	14.4	8	0.000	F=4.81 $p \leq 0.05$		→
TURN PULLOUT	135.6	99.2	8	0.316	78.8	34.6	8	0.001	F=8.22 $p \leq 0.01$		→
RECOVERY WITH CROSSCURRENT	22.4	114.4	8	0.094	86.1	53.5	8	0.021	F=4.57 $p \leq 0.05$		→
TRACKKEEPING WITH CROSSCURRENT	7.5	46.1	8	0.000	53.2	34.6	8	0.000	F=1.77 N.S.	t=2.24	←

KEY:

□ NO STATISTICAL DIFFERENCES

⇨ STATISTICAL DIFFERENCE AT $p \leq 0.10$ level

➡ STATISTICAL DIFFERENCE AT $p \leq 0.05$ level

DIRECTION OF ARROW POINTS TO THE BETTER CONDITION (RIGHT OR LEFT COLUMN).

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